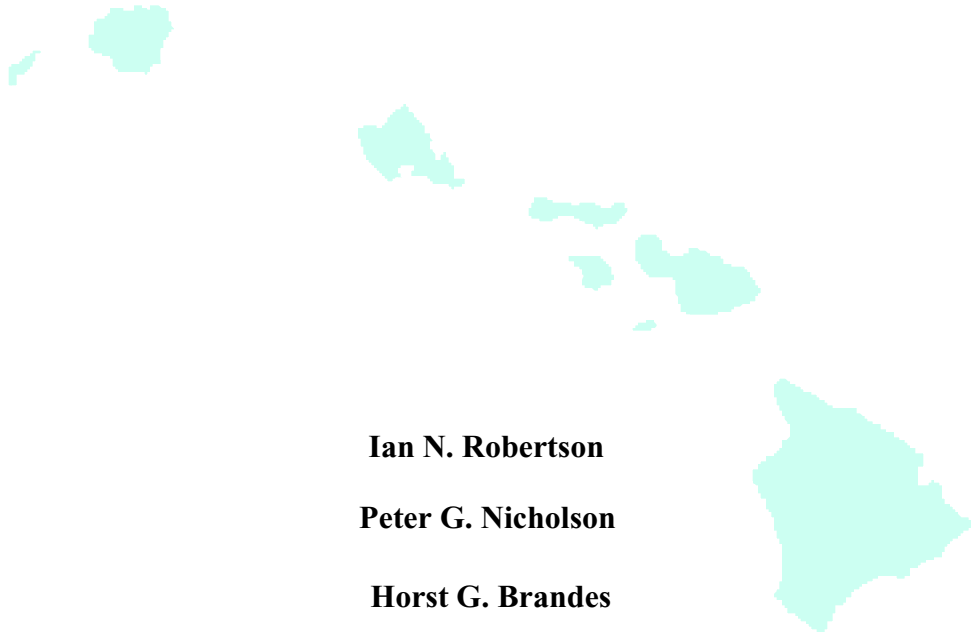


**Reconnaissance Following the October 15th, 2006
Earthquakes on the Island of Hawai'i**



Ian N. Robertson

Peter G. Nicholson

Horst G. Brandes



**UNIVERSITY OF HAWAII
COLLEGE OF ENGINEERING**

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Research Report UHM/CEE/06-07

October 26, 2006

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Executive Summary

On October 15th, 2006, two earthquakes with magnitudes of Mw6.7 and Mw6.0 struck in close succession just off the Northwest coast of the Island of Hawai`i. No deaths were attributed to ground shaking, and only minor injuries were reported, including two broken bones. Damage caused by these earthquakes had exceeded \$100 million as of the writing of this report, without including damage to private residences. It is likely that the total cost of these earthquakes will exceed \$200 million. This is significantly less than the \$17.8 billion in damages caused by the similar magnitude 6.7 Northridge earthquake in the Los Angeles area in 1994. The low injury rate and economic loss is attributed to the relatively rural area in which the Kiholo Bay and Hawi earthquakes struck, and the relatively large 40 km (25 miles) focal depth of the M6.7 Kiholo Bay earthquake. It was also fortunate that the earthquakes struck just after sunrise on a Sunday morning.

Overall, the vast majority of built infrastructure in the vicinity of the earthquake epicenters survived with little or no apparent damage. Recorded ground accelerations show a maximum horizontal ground acceleration of 1.03g and a maximum vertical ground acceleration of 0.72g at the Waimea fire station, about 32 km (20 miles) from the Kiholo Bay earthquake epicenter. Shaking reached Intensity VIII on the Modified Mercalli Scale (MMI) as reported by residents. Strong ground motions lasted for approximately 20 seconds during the Kiholo Bay earthquake, and 15 seconds during the Hawi earthquake.

Structural damage occurred at a number of buildings, bridges and port facilities, particularly those closest to the earthquake epicenters. Much of the damage to buildings was in the form of failure of non-structural elements such as ceilings, light fixtures, plumbing and other utility lines. Although over 1,800 individual residences were damaged to varying degrees, tens of thousands of light-framed timber homes in neighborhoods close to the epicenters survived with virtually no damage. The provision of shear walls and continuous load-path for hurricane wind design may have contributed to the superior seismic performance of some of these residences. Many of the homes that were destroyed or experienced severe damage were constructed on pier-and-beam foundation systems resting on small loose concrete foundation blocks. The ground shaking resulted in lateral movement of the posts off these substandard foundations resulting in moderate to complete damage to the residence. Longer duration or more intense ground shaking would likely have caused significantly more damage to residential structures elevated on pier-and-beam framing.

Numerous rockfalls and slides occurred in road cuts, embankments and natural slopes. The extent of these failures diminished considerably toward the more populated centers of Hilo and Kailua-Kona. Because of the lack of redundancy in the highway system on Hawai`i Island, road closures due to rockfalls or landslides can have a devastating effect

on emergency response and economic recovery efforts. For a number of hours after the earthquakes, the area of North Kohala, including the town of Hawi, was cut off from the rest of the island because of road closures on Highways 250 and 270, the only access roads to this region. Fortunately, the rockfalls and landslides caused by these earthquakes could be cleared relatively easily, and all roadways were open to at least one-lane traffic within a day or two of the earthquakes. It was noted that wide shoulders on Highway 19 North of Kailua-Kona were able to accommodate much of the rockfall material without encroaching on the driving lanes.

Some damage occurred to dams and irrigation ditches in the Waimea-Kamuela area. Two dams experienced earth fill disturbance and cracks along their crests, while at least two others showed clear evidence of incipient slope failure on their embankments. A system of irrigation ditches feeding some of these reservoirs was interrupted due to debris blockage. Roadway embankments were affected at a series of locations, in one case resulting in the collapse of a traffic lane on the approach to a bridge. A few retaining walls collapsed, primarily poorly-built, un-reinforced and un-mortared rock walls.

One of the two major commercial ports on the island, Kawaihae Harbor, sustained major damage from liquefaction and lateral spreading. This facility is located less than 24 km (15 miles) from both earthquake epicenters. Much of the fill material under the shipping container handling yard consists of dredged fill. As this material liquefied, the resulting lateral spreading caused significant vertical settlement of the asphalt pavement, and lateral displacement of the pile supported concrete piers. Large torsional cracks in the reinforced concrete edge beam of one of the two pile-supported piers, Pier 1 (North pier), were attributed to this lateral movement. It is unknown at the time of writing this report if any damage had been incurred by the piles supporting this pier. Pier 1 remains closed indefinitely.

The lateral spreading also resulted in deformation of the pre-manufactured metal frame warehouses adjacent to the concrete piers. Although damage to these buildings is relatively minor, the potential remains for further liquefaction of the fill materials during future earthquakes. No damage was noted at Hilo Harbor on the East side of the island, however it is known that much of the harbor is constructed on fill materials that are susceptible to liquefaction.

Because Hilo and Kawaihae Harbors are the only two ports on Hawai'i Island capable of handling the barges that transport most of the island's supplies from Honolulu Harbor, they are an essential lifeline for the inhabitants of the island. Remedial measures should be taken to replace or stabilize any fill material with liquefaction potential in critical harbor facilities to avoid loss of function of either of these ports during future earthquakes.

Acknowledgements

The authors wish to acknowledge the assistance of a number of individuals in the collection of data for this report. Jeanne Johnston of Hawaii State Civil Defense provided initial damage location reports; Gary Chock and Glenn Miyasato provided feedback from structural inspections along the Kona coast; Afaq Sarwar provided information on structural inspections of numerous residences around Waimea; Paul Okubo of Hawaii Volcano Observatory assisted with ground motion interpretation; Brennon Morioka of the State Department of Transportation provided input on the Route 19, 35 milemarker, bridge approach collapse; and Andrew Stout of Natural Resources Conservation Service (NRCS) and Robert Masuda of the Department of Land and Natural Resources (DLNR) provided access to reservoirs in the Waimea area. Gary Chock, Paul Okubo and Afaq Sarwar also provided helpful review comments on a draft of this report.

Funding for this reconnaissance trip was provided by the Department of Civil and Environmental Engineering at the University of Hawaii at Manoa. This support is gratefully acknowledged.

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Introduction

Two earthquakes and numerous aftershocks struck the Northwest Coast of the Island of Hawai'i (a.k.a. The Big Island) on October 15th, 2006. The Kiholo Bay earthquake, with a Magnitude of Mw6.7, struck at 7.07 AM local time (17.07 UTC) with epicenter location at 19.878 N, 155.935 W, and focal depth of approximately 39 km (24 miles). It was followed by the Hawi earthquake with a Magnitude of Mw6.0 at 7.14 AM local time (17.14 UTC) with epicenter location at 20.129 N, 155.983 W, and focal depth of approximately 19 km (12 miles) (USGS Website, 2006a). The Hawi earthquake is considered a separate event and not an aftershock because of the distinct source location, though it was likely triggered by the larger Kiholo Bay earthquake. Figure 1 shows the USGS-determined epicenter locations relative to the Island of Hawai'i.

The Kiholo Bay earthquake was unusual for its location and depth. It is not associated with any well known fault system but is probably related to tectonic flexing of the oceanic crust beneath the Big Island volcanic edifice as a result of continued island growth.

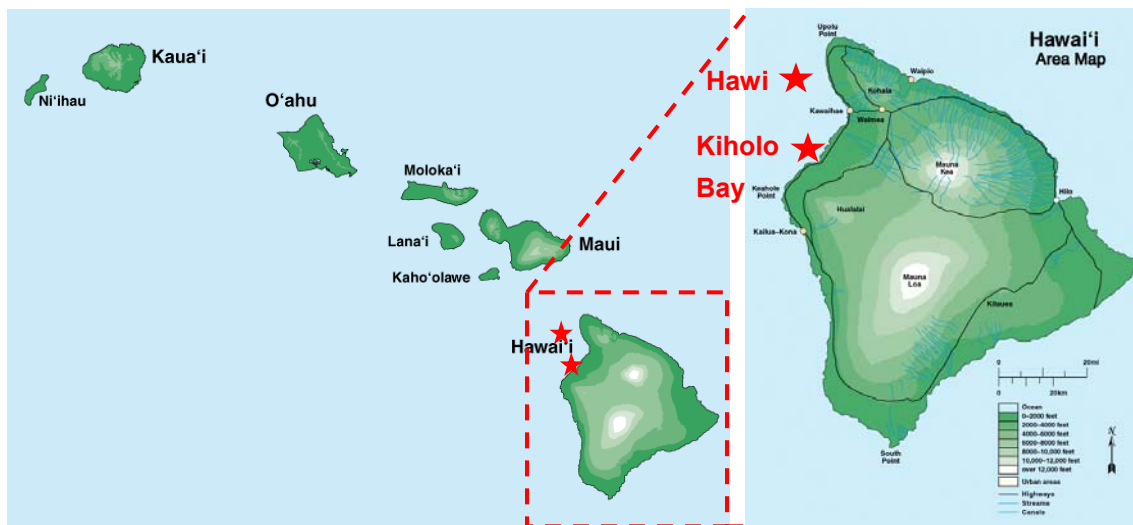


Figure 1: Epicenter locations of Kiholo Bay and Hawi Earthquakes

The effects of the earthquakes were felt on all islands in the State of Hawai'i. Figure 2 shows the USGS Community Internet Intensity Map for the Kiholo Bay earthquake based on 2,900 individual reports received during the week following the earthquakes. It is likely that this map reflects the public response to both Kiholo Bay and Hawi earthquakes since the Hawi earthquake was initially perceived as an aftershock. The maximum Mercalli Intensity VIII was reported close to the Hawi epicenter, and personal communications with residents of the Hawi area indicate that its effects in their area were as severe as, or even worse than, those of the Kiholo Bay event. The shallow

hypocenter location would likely have increased the local effects of this smaller magnitude event, while the effects at distant locations would have been reduced.

USGS Community Internet Intensity Map (10 miles NNW of Kailua Kona, Hawaii, Hawaii)
ID:twbh_06 07:07:48 HST OCT 15 2006 Mag=6.7 Latitude=N19.88 Longitude=W155.94

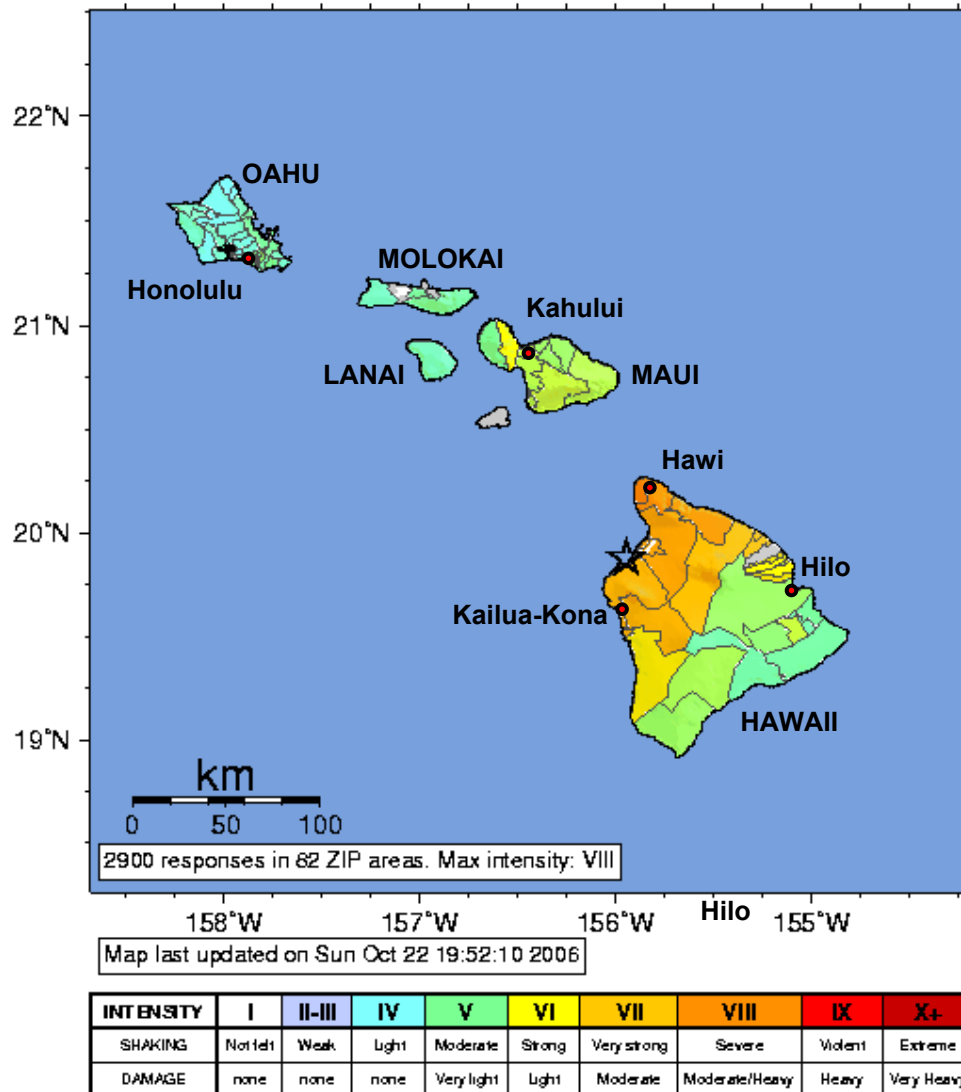


Figure 2: USGS Community Internet Intensity Map for Hawai'i Islands

Damage to built infrastructure as a result of these two earthquakes was concentrated primarily along the Kona coast (West coast) and in the Kohala region (North) on the island of Hawai'i. However, significant damage also occurred on the Hamakua coast of Hawai'i Island (Northeast coast), and the Southeast end of Maui. Minor damage to

buildings was reported in areas further afield, including Honolulu, Oahu. A significant aftermath of the earthquakes was the loss of electrical power to much of the Island of Hawaii, Maui County and the entire island of Oahu. Power was only restored to a majority of customers 12 hours after the earthquakes. It was fortunate that the earthquakes occurred early on a Sunday morning, so that disruption due to the extended power loss was not as severe as it could have been during a week day or during overnight hours.

The location of the epicenters just offshore from relatively rural areas significantly reduced the potential for loss of life, injury and property damage that could be expected from earthquakes of this magnitude. The 40 km deep hypocenter of the Mw 6.7 Kiholo Bay earthquake also appears to have reduced the consequences at ground level. At the time of the writing of this report, no deaths had been attributed to the ground shaking, and only 25 injuries were reported, including 2 broken bones, none requiring hospitalization. Damage reports for public buildings and infrastructure as of October 21 were published by the Honolulu Advertiser as indicated in Table 1. Repair costs for private residences had not yet been estimated.

Table 1: Damage Reports as of October 21st, 2006

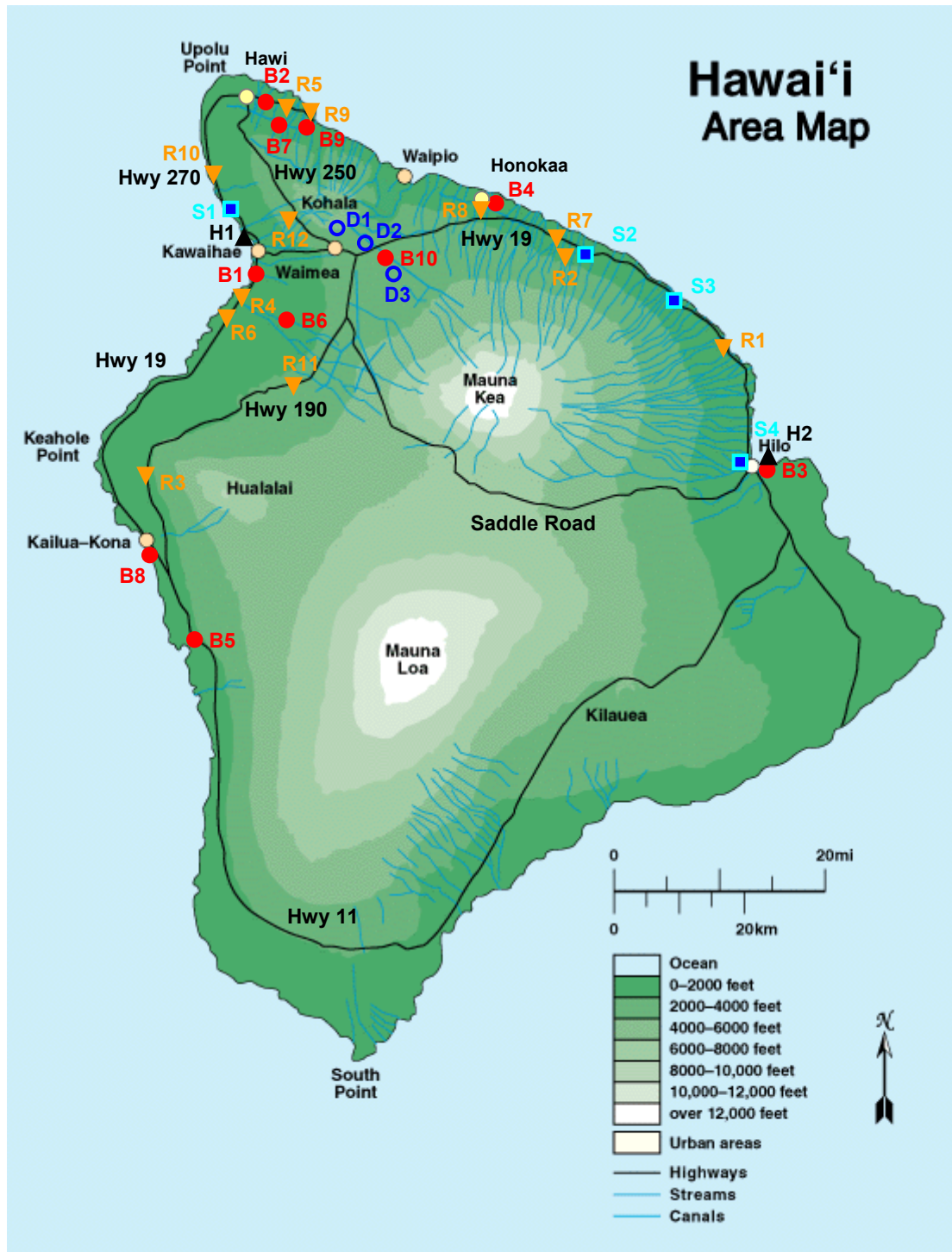
Category	Major Damage	Minor Damage	Estimated Cost (\$ millions)
• Hawaii County Buildings	15	7	} \$3.7
• Hawaii State Buildings	10	6	
• Public Schools	4	25	\$43.5
• Hospitals	2	2	\$10.0
• Private Businesses	36	264	\$13.8
• Private Residences	162	1705	No Estimate
• Hawaii County Bridges			\$0.2
• Hawaii State Bridges			\$7.25
• Hawaii County Roads			\$2.4
• Hawaii State Roads			\$7.87
• Harbors	1	0	\$7.0
• Electric Utility			\$4.0
• Agricultural Damage			\$0.8
Total Estimated Losses (as of October 21, 2006)			\$100.52

This estimate does not include the cost of repairing or replacing damaged private residences. Reports list 10 homes as totally destroyed, 152 with major damage, 1,475 with minor damage requiring immediate repair, and 230 with minor damage not requiring immediate repair (Honolulu Advertiser, Oct. 21, 2006). It also does not include repair

and strengthening work planned for water reservoirs (Honolulu Advertiser, Oct. 22, 2006) or any estimate of economic loss due to business interruption. The total cost of the earthquakes is therefore expected to increase considerably when these elements are included.

A HAZUS analysis of the Kiholo Bay earthquake was performed by the Pacific Disaster Center (PDC) on behalf of the State Civil Defense (SCD) sponsored Hawaii State Earthquake Advisory Committee (HSEAC) shortly after the event. Utilizing a locally validated building inventory database, attenuation function (Munson and Thurber, 1997) along with a 0.4 magnitude reduction based on prior event calibration, HAZUS predicted 1 death, 1 critical injury, 11 hospitalizations and 69 minor injuries. HAZUS predictions of economic losses totaled \$264 million for building loss and \$70 million for business interruption loss. Given that the earthquakes occurred on a Sunday, the business interruption loss will likely be less than predicted.

This report details observations made by an earthquake reconnaissance team from the Civil and Environmental Engineering Department at the University of Hawaii at Manoa. The team consisted of Ian Robertson, Professor of Structural Engineering, and Peter Nicholson and Horst Brandes, Associate Professors of Geotechnical Engineering. The team visited over 40 sites during Tuesday and Wednesday following the earthquakes (October 17 and 18). The assessment focused on areas North of Kailua-Kona and North of Hilo, where most of the damage was reported. Selected ground motion records in Appendix A suggest substantially lower shaking levels toward the southern half of the island. The observations made during this reconnaissance trip are presented in five broad categories, namely Buildings, Bridges, Harbors, Dams and Roadways. In each of these categories, critical infrastructure issues such as emergency access, power, water supply and other lifeline systems are covered as appropriate. The locations of all sites referenced in this report are indicated in Figure 3. Each photograph in this report is cross-referenced to a colored location marker in Figure 3. Also shown in Figure 3 are all major highways on the Island. There is a significant lack of redundancy in the highway network. Road closures due to rockfalls, landslides, embankment or bridge failure can have a tremendous impact on emergency response and economic recovery.



●B1-10: Buildings ■S1-4: Bridges ▲H1-2: Harbors ○D1-3: Dams ▼R1-R12: Roadways

Figure 3: Location of sites referenced in this report

Seismology

A limited array of 12 dialup strong motion (SM) instruments on the Island of Hawai'i automatically transmitted records to a USGS server in Menlo Park (Figure 4). These records are available for download from the USGS website at http://nsmp.wr.usgs.gov/data_sets/20061015_1707.html for the Kiholo Bay earthquake, and at http://nsmp.wr.usgs.gov/data_sets/20061015_1714.html for the Hawi earthquake. No SM records are available from Hawi and surrounding areas in North Kohala. Strong motion records for the Kiholo Bay earthquake as recorded at Waimea, Honokaa, Kailua-Kona and Hilo, and records for the Hawi earthquake recorded at Waimea, are included in Appendix A.

Site characterization has not been performed at the locations of these strong motion instruments, leading to some uncertainty as to the interpretation of the records. The maximum horizontal accelerations for both earthquakes as recorded at Waimea Fire Station are shown in Figure 5. The maximum horizontal accelerations for the Kiholo Bay earthquake as recorded at Honokaa, Kailua-Kona and Hilo are shown in Figure 6. The Peak Ground Acceleration (PGA) from each of the 12 SM stations are listed in Table 2 for the Kiholo Bay earthquake, and Table 3 for the Hawi earthquake.

Horizontal and vertical PGAs of 1.03g and 0.72g, respectively, were recorded at the Waimea Fire Station during the Kiholo Bay earthquake. Horizontal and vertical PGAs of 0.64g and 0.35g, respectively, were recorded at the Honokaa Fire Station while horizontal and vertical PGAs of 0.51g and 0.28g, respectively, were recorded at the Kona Hospital in Kealahou, South of Kailua-Kona. The maximum horizontal and vertical PGAs recorded in the Hilo area on the East side of the island were 0.23g and 0.1g, respectively, at the USDA laboratory station. Ground shaking records were significantly lower at all 12 stations for the Hawi earthquake. At the time of the writing of this report, strong motion data was not yet available from any stations on Maui or other Hawai'i stations that use film recorders that must be collected and interpreted manually.

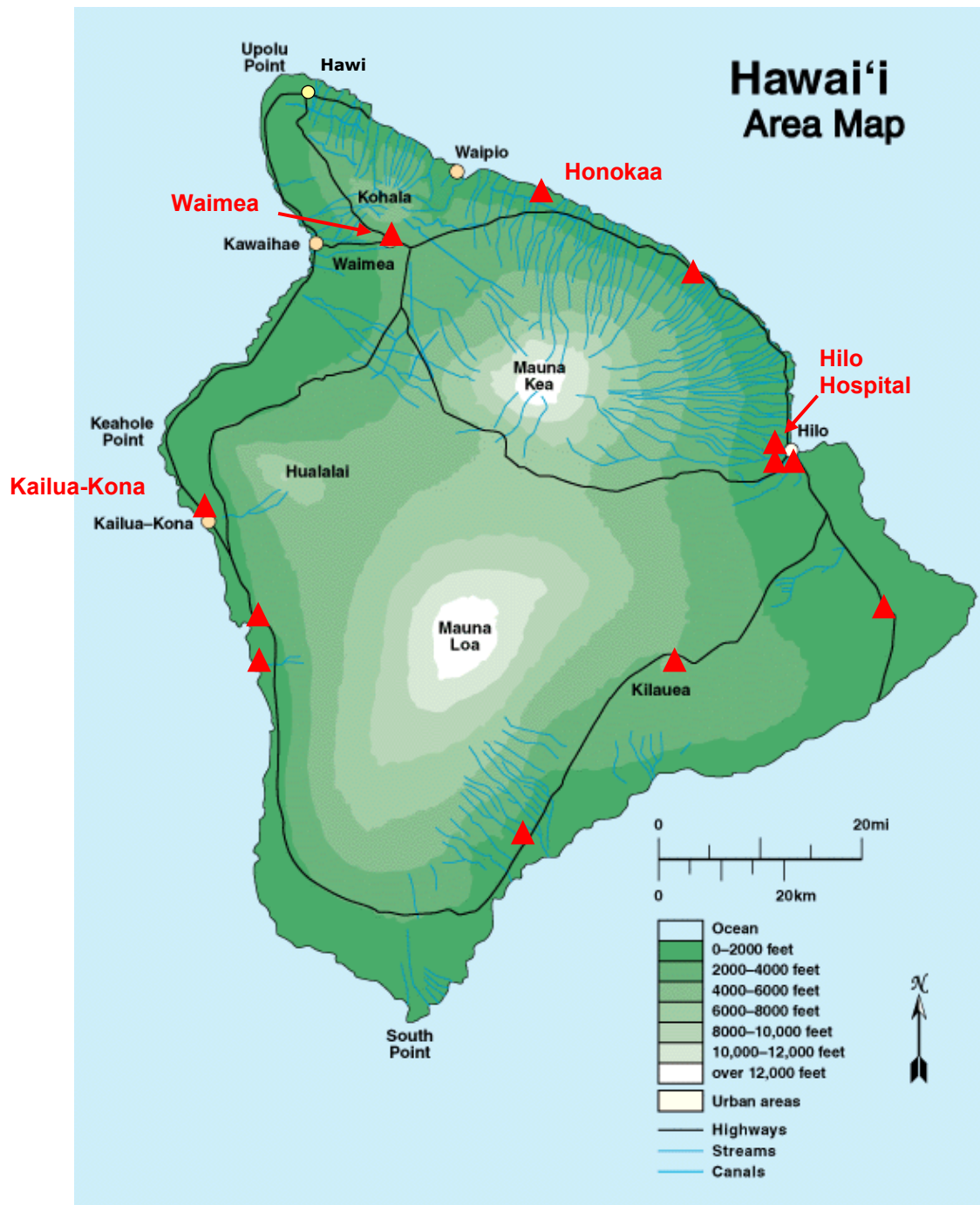


Figure 4: Locations of ANSS Dialup Strong Motion Instruments

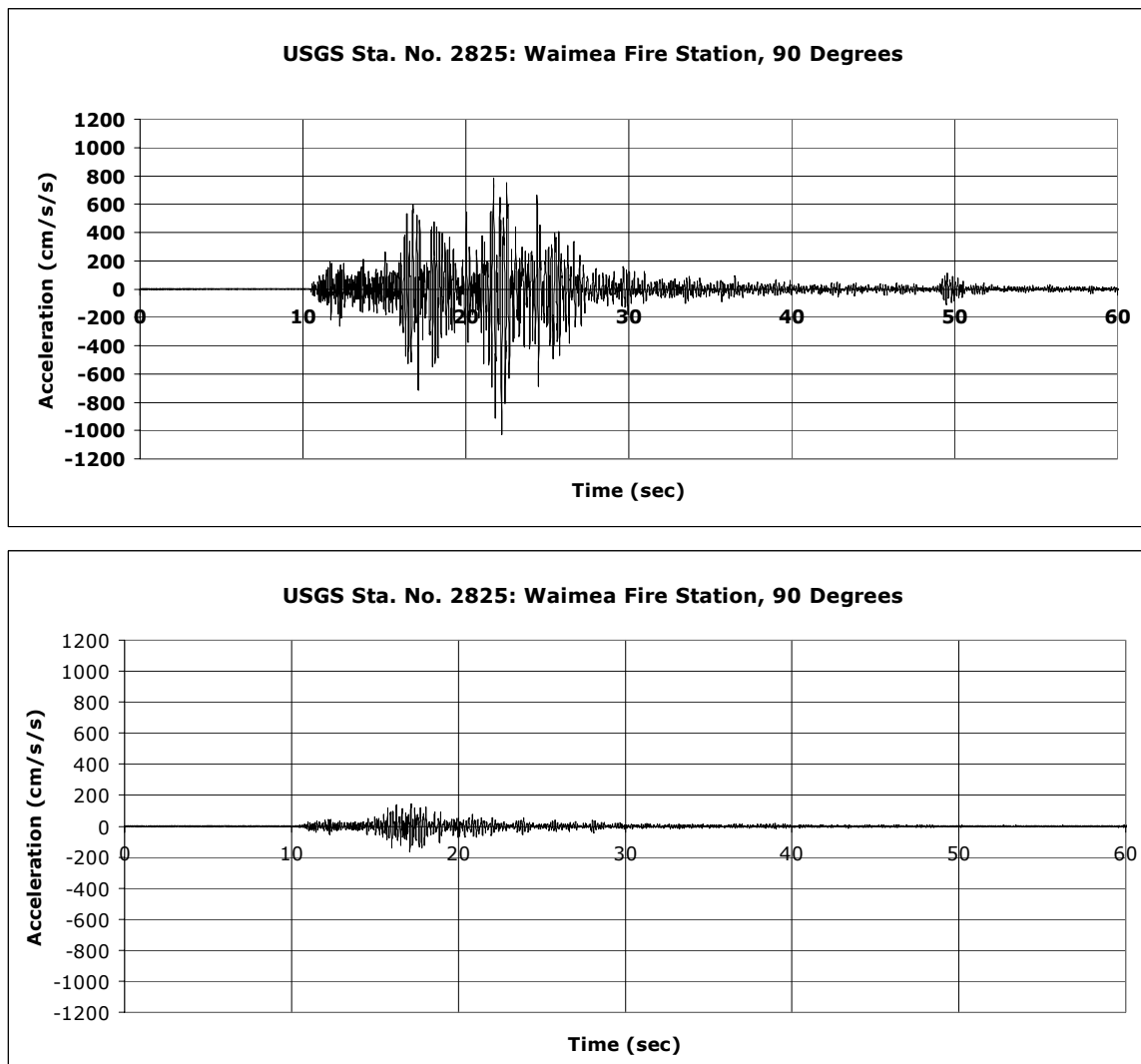


Figure 5: Ground accelerations recorded at Waimea Fire Station during the Mw 6.7 Kiholo Bay (top) and Mw 6.0 Hawi (bottom) earthquakes.

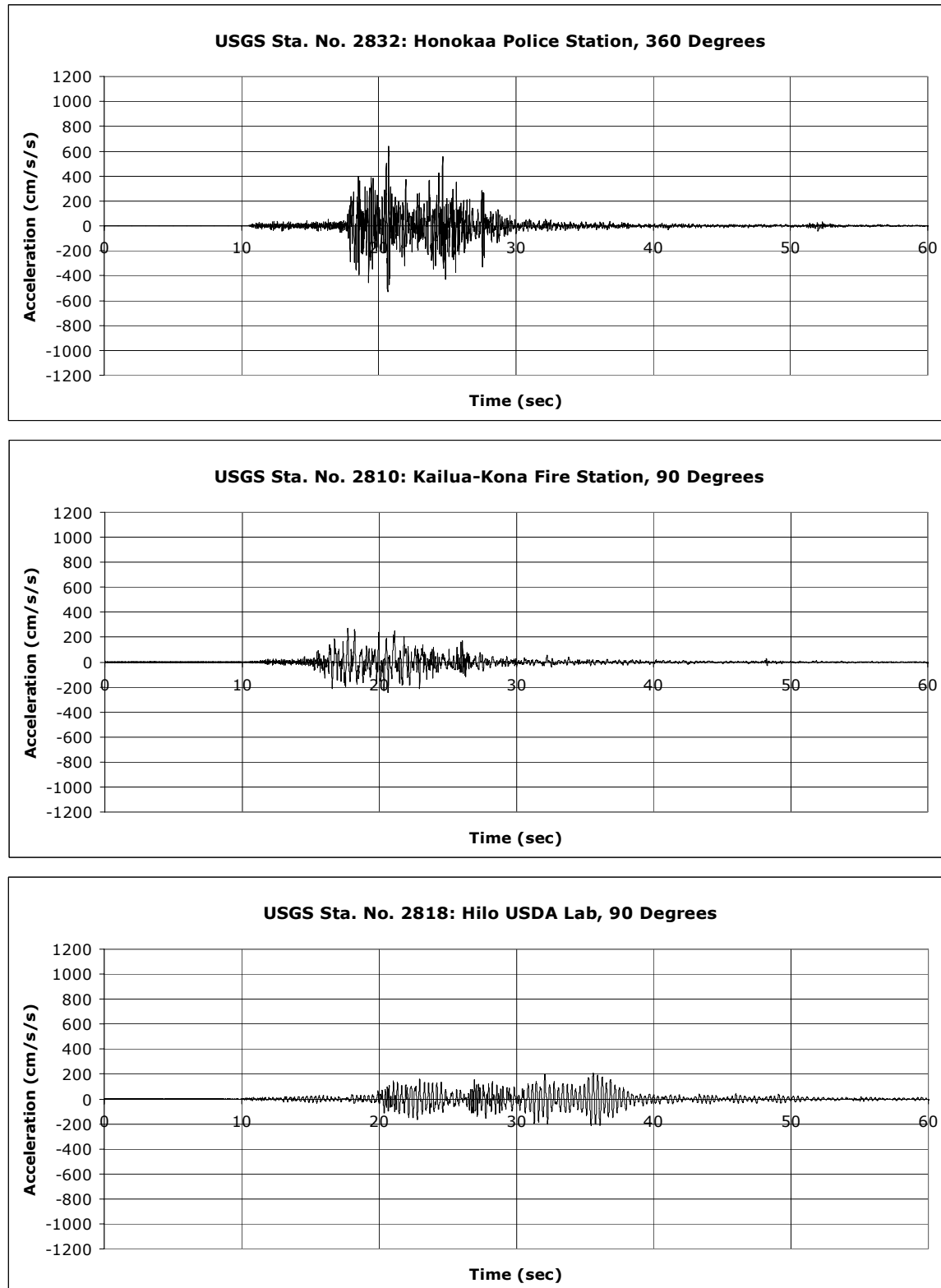


Figure 6: Selected ground accelerations recorded at Honokaa (top), Kailua-Kona (middle) and Hilo (bottom) during the Mw 6.7 Kiholo Bay earthquake

Table 2: USGS National-Strong Motion Program – Kiholo Bay Earthquake
**Preliminary Corrected Peak Ground Acceleration and Velocity and Pseudo-Spectral Acceleration Values for
October 15, 2006, Kiholo Bay, Hawai'i Island, HI Earthquake (posted 10/16/2006)**

Mw 6.6, 10/15/2006, 17:07 UTC, 10/15/2006, 07:17 AM HST, 19.878 N, 155.935 W, 38.90 km depth, Regional Network ID# ustwbh

Sta	Inst	Inst	State: City; Recorder Location	Owner	Lat	Lon	Dist	Az	Ch	Sensor	Orient	PGA	PGV	PSA at:		
No	type	S/N			deg	deg	km	deg	No	type	deg	cm/s/s	cm/s	0.3 s	1.0 s	3.0 s
2810	Etna	1988	HI:Kailua-Kona, Hawai'i Is; Fire Sta	USGS	19.6477	-155.9923	26.2	193	1	EpiSen	90	268	18.90	95.5	22.20	2.06
									2	EpiSen	360	-259	13.60	59.6	9.58	1.90
									3	EpiSen	UP	233	-6.24	17.7	4.77	0.94
2825	K2	2000	HI:Waimea, Hawai'i Is; Fire Station	USGS	20.0230	-155.6614	32.8	61	1	EpiSen	90	-1030	42.00	165.0	18.50	1.10
									2	EpiSen	360	673	27.90	117.0	15.70	2.06
									3	EpiSen	UP	723	-20.00	64.1	8.32	1.12
2849	K2	1810	HI:KeaLakekua, HI;Kona Hospital	USGS	19.5215	-155.9181	39.5	177	1	EpiSen	90	508	14.00	59.0	8.81	1.92
									2	EpiSen	360	-362	-10.70	38.9	5.37	1.13
									3	EpiSen	UP	283	-4.79	16.4	1.76	0.57
2845	K2	1848	HI:Honaunau, Hawai'i Is; PO	USGS	19.4174	-155.8805	51.3	174	1	EpiSen	90	197	8.36	57.1	5.79	1.40
									2	EpiSen	360	-182	9.45	39.4	6.50	1.32
									3	EpiSen	UP	114	3.12	8.8	1.45	0.42
2832	K2	1819	HI:Honokaa, Hawai'i Is; Police Sta	USGS	20.0775	-155.4625	54.2	66	1	EpiSen	90	-640	14.80	60.7	13.10	0.80
									2	EpiSen	360	639	24.80	72.6	21.30	1.97
									3	EpiSen	UP	-350	-7.92	21.7	6.87	0.80
2833	K2	1849	HI:Laupahoehoe, Hawai'i Is; PO	USGS	19.9835	-155.2326	74.5	81	1	EpiSen	90	311	9.23	42.6	8.18	0.93
									2	EpiSen	360	-350	14.00	33.2	10.40	0.91
									3	EpiSen	UP	-196	4.47	19.9	3.65	0.52
2836	Etna	1984	HI:Volc Nat'l Pk, HI; HVO Svc	USGS	19.420	-155.288	84.7	127	1	EpiSen	90	-56	6.01	15.1	6.36	2.00
									2	EpiSen	360	58	5.48	13.0	10.30	1.16
									3	EpiSen	UP	34	-1.86	6.7	2.03	0.76
2839	K2	1853	HI:Hilo, Hawai'i Is; Old Hospital	USGS	19.722	-155.115	87.6	101	1	EpiSen	90	-76	3.89	19.0	3.92	0.79
									2	EpiSen	360	54	-3.67	14.0	5.75	0.55
									3	EpiSen	UP	-32	-2.15	8.9	2.47	0.44
2818	K2	1855	HI:Hilo, Hawai'i Is; USDA Lab	USGS	19.7277	-155.0974	89.3	101	1	EpiSen	90	-215	-12.70	126.0	9.67	1.02
									2	EpiSen	360	232	13.50	116.0	9.03	0.70
									3	EpiSen	UP	-97	-3.25	10.4	2.18	0.42
2812	K2	1850	HI:Pahala, Hawai'i Is; Ka'u Hospital	USGS	19.1999	-155.4723	89.4	147	1	EpiSen	90	123	4.73	24.9	4.98	0.74
									2	EpiSen	360	176	7.17	24.0	5.41	1.07
									3	EpiSen	UP	-91	2.58	16.5	1.52	0.24
2817	Etna	1985	HI:Hilo, Hawai'i Is; Univ of Hawaii	USGS	19.7034	-155.0805	91.6	102	1	EpiSen	90	58	-4.88	13.6	7.38	0.99
									2	EpiSen	360	-45	-5.38	8.5	10.40	0.42
									3	EpiSen	UP	-30	-1.64	4.4	2.29	0.35
2816	Etna	1986	HI:Pahoa, Hawai'i Is; Fire Station	USGS	19.4934	-154.9466	112.0	112	1	EpiSen	90	64	3.22	11.4	3.52	0.53
									2	EpiSen	360	83	-3.11	18.4	4.57	0.56
									3	EpiSen	UP	29	-1.11	4.8	1.52	0.27

Table 3: USGS National-Strong Motion Program – Hawi Earthquake
**Preliminary Corrected Peak Ground Acceleration and Velocity and Pseudo-Spectral Acceleration Values for
October 15, 2006, Hawi, Hawai'i Island, HI Earthquake (posted 10/17/2006)**

Mw 6.0, 10/15/2006, 17:14 UTC, 10/15/2006, 07:14 AM HST, 20.129 N, 155.983 W, 18.90 km depth, Regional Network ID# ustwbi

Sta No	Inst type	Inst S/N	State: City; Recorder Location	Owner	Lat deg	Lon deg	Dist km	Az deg	Ch No	Sensor type	Orient deg	PGA cm/s/s	PGV cm/s	PSA at:		
														0.3 s	1.0 s	3.0 s
2825	K2	2000	HI:Waimea, Hawai'i Is; Fire Station	USGS	20.0230	-155.6614	35.6	109	1	EpiSen	90	-166.0	-3.92	9.2	2.40	0.265
									2	EpiSen	360	128.0	4.90	9.7	4.79	0.706
									3	EpiSen	UP	-129.0	-3.15	6.0	2.83	0.346
2810	Etna	1988	HI:Kailua-Kona, Hawai'i Is; Fire Sta	USGS	19.6477	-155.9923	53.3	181	1	EpiSen	90	-29.1	-3.10	6.9	2.87	0.782
									2	EpiSen	360	59.3	-6.19	13.9	4.69	0.566
									3	EpiSen	UP	-19.0	0.95	2.7	1.14	0.570
2832	K2	1819	HI:Honokaa, Hawai'i Is; Police Sta	USGS	20.0775	-155.4625	54.7	96	1	EpiSen	90	28.3	1.24	3.2	0.85	0.321
									2	EpiSen	360	-33.0	-1.51	2.4	1.10	0.372
									3	EpiSen	UP	29.3	0.54	1.8	0.39	0.151
2849	K2	1810	HI:KeaLakekua, HI;Kona Hospital	USGS	19.5215	-155.9181	67.6	174	1	EpiSen	90	16.6	1.50	3.5	1.39	0.371
									2	EpiSen	360	-25.1	-1.89	3.9	1.70	0.627
									3	EpiSen	UP	-13.6	-0.69	1.6	0.95	0.435
2845	K2	1848	HI:Honaunau, Hawai'i Is; PO	USGS	19.4174	-155.8805	79.5	172	1	EpiSen	90	-53.7	1.70	8.1	1.84	0.417
									2	EpiSen	360	46.6	-2.38	13.0	1.55	0.206
									3	EpiSen	UP	25.3	-0.87	3.0	1.14	0.170
2833	K2	1849	HI:Laupahoehoe, Hawai'i Is; PO	USGS	19.9835	-155.2326	80.1	101	1	EpiSen	90	18.2	-0.87	2.3	0.90	0.278
									2	EpiSen	360	-22.0	-0.83	2.6	1.11	0.346
									3	EpiSen	UP	14.7	0.39	1.0	0.45	0.117
2839	K2	1853	HI:Hilo, Hawai'i Is; Old Hospital	USGS	19.722	-155.115	101.4	116	1	EpiSen	90	-5.8	0.77	1.9	1.52	0.326
									2	EpiSen	360	-7.8	0.76	2.0	0.60	0.285
									3	EpiSen	UP	4.1	0.40	0.5	0.32	0.242
2818	K2	1855	HI:Hilo, Hawai'i Is; USDA Lab	USGS	19.7277	-155.0974	102.8	115	1	EpiSen	90	-28.9	-1.62	16.6	0.92	0.282
									2	EpiSen	360	29.1	-1.70	11.8	0.86	0.282
									3	EpiSen	UP	13.7	0.50	1.1	0.27	0.163
2817	Etna	1985	HI:Hilo, Hawai'i Is; Univ of Hawaii	USGS	19.7034	-155.0805	105.6	116	1	EpiSen	90	7.7	-0.92	1.9	1.51	0.420
									2	EpiSen	360	-6.0	0.81	1.0	1.10	0.272
									3	EpiSen	UP	-3.4	-0.37	0.4	0.37	0.213
2836	Etna	1984	HI:Volc Nat'l Pk, HI; HVO Srv	USGS	19.420	-155.288	107.1	137	1	EpiSen	90	12.2	-2.15	1.7	4.04	0.938
									2	EpiSen	360	21.4	-2.68	2.9	6.73	0.592
									3	EpiSen	UP	4.6	0.47	0.9	0.92	0.133
2812	K2	1850	HI:Pahala, Hawai'i Is; Ka'u Hospital	USGS	19.1999	-155.4723	116.0	152	1	EpiSen	90	25.0	1.11	1.9	1.49	0.281
									2	EpiSen	360	18.0	-0.78	2.4	1.23	0.315
									3	EpiSen	UP	10.9	-0.55	0.8	0.69	0.273
2816	Etna	1986	HI:Pahoa, Hawai'i Is; Fire Station	USGS	19.4934	-154.9466	129.4	123	1	EpiSen	90	5.8	-1.02	0.9	0.85	0.619
									2	EpiSen	360	-4.7	0.83	0.8	1.10	0.314
									3	EpiSen	UP	2.0	-0.38	0.4	0.42	0.177

The strong motion records were incorporated into the USGS "ShakeMap" for the Kiholo Bay earthquake shown in Figure 7.

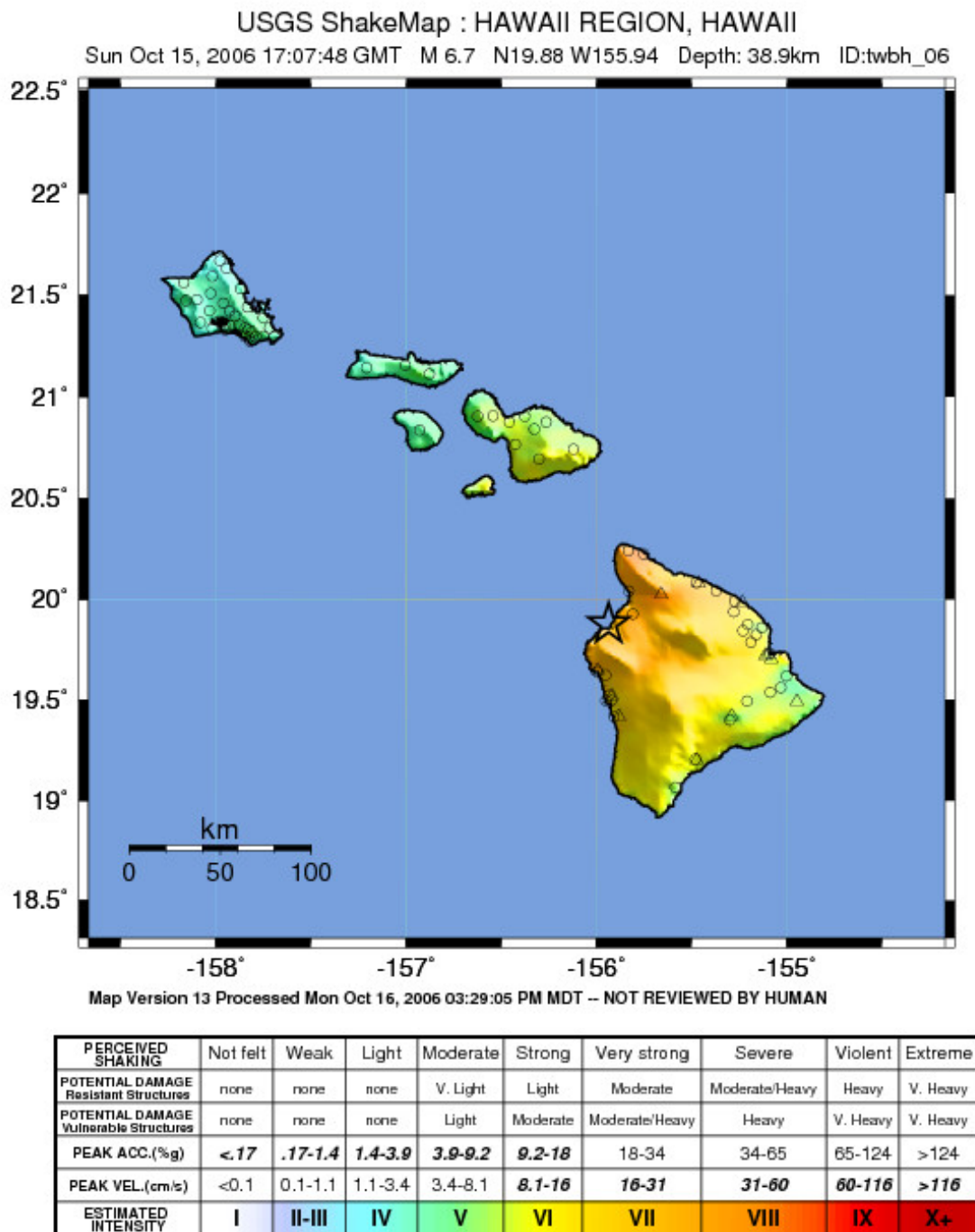


Figure 7: USGS "ShakeMap" for the Kiholo Bay Earthquake

Buildings

Numerous buildings were damaged by the ground shaking resulting from the two October 15th earthquakes. It is not known how much of the damage was caused by each individual earthquake, so damage records provided here are the cumulative effect of the two events. Building damage was reported as far afield as the Manoa Valley Inn in Manoa, Oahu, where a rock-masonry chimney collapsed, and Iolani Palace in downtown Honolulu, Oahu, where cracking occurred in the interior stucco ceiling and wall finishes. Building damage was also reported on the islands of Maui, Lanai and Molokai, though none was inspected as part of this reconnaissance trip.

The buildings reported below are separated into engineered and non-engineered structures. Most were inspected by our team, though some details were provided by other inspectors as noted below.

Engineered Buildings

Mauna Kea Hotel

The Mauna Kea Hotel is located on the shoreline just 11 miles from the Kiholo Bay earthquake epicenter. A reinforced concrete trellis structure above the South wing of the hotel collapsed as shown in Figure 8. Damage to a balcony below this structure was probably the result of impact from falling debris (Figure 9). This failure is attributed to combined vertical and horizontal ground shaking causing separation of the precast trellis elements from the supporting cast-in-situ cantilever beams. Fortunately, no injuries resulted from this collapse.

Figure 10 and Figure 11 show significant damage to the concrete surrounding two connector plates between a precast exhaust flume and an elevator shear wall. The U-shaped exhaust flume was added to the South side of the existing shear wall as part of a hotel expansion. The majority of the hotel is still operational.



Figure 8: Collapse of concrete trellis frame at Mauna Kea Hotel (B1).



Figure 9: Damage to balcony due to impact from falling debris (B1).

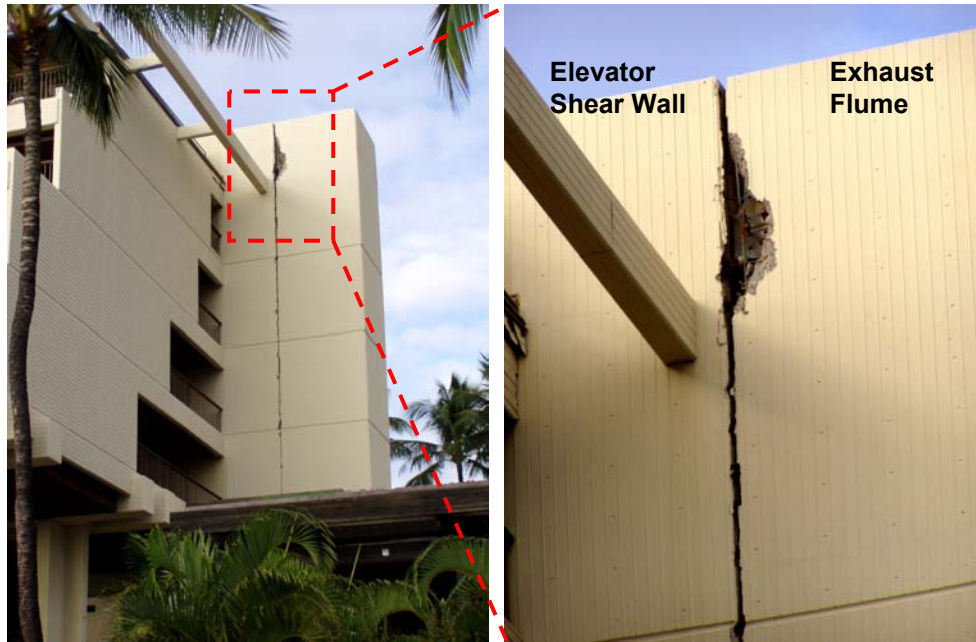


Figure 10: Damage to concrete flume at connector plate – Makai (Ocean) side (B1).

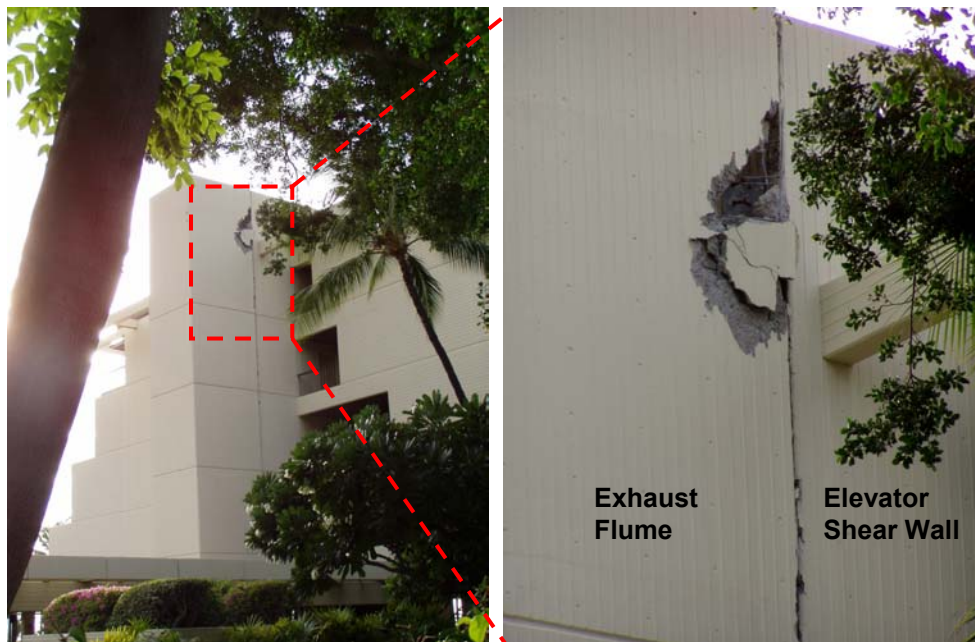


Figure 11: Damage to concrete flume at connector plate – Mauka (Mountain) side (B1).

Bank of Hawaii, Kapaau (Near Hawi)

The reinforced concrete walls of this single-story bank building support timber roof trusses spanning between the side walls. The ends of the roof trusses are pocketed into the side walls. Horizontal cracks developed at the level of these roof truss pockets and diagonal cracks occurred at the buildings corners (Figure 12). Lack of adequate diaphragm action at the roof level is thought to have allowed significant out-of-plane

movement of the side walls (personal communication with Gary Chock). The bank is closed until repairs can be made.

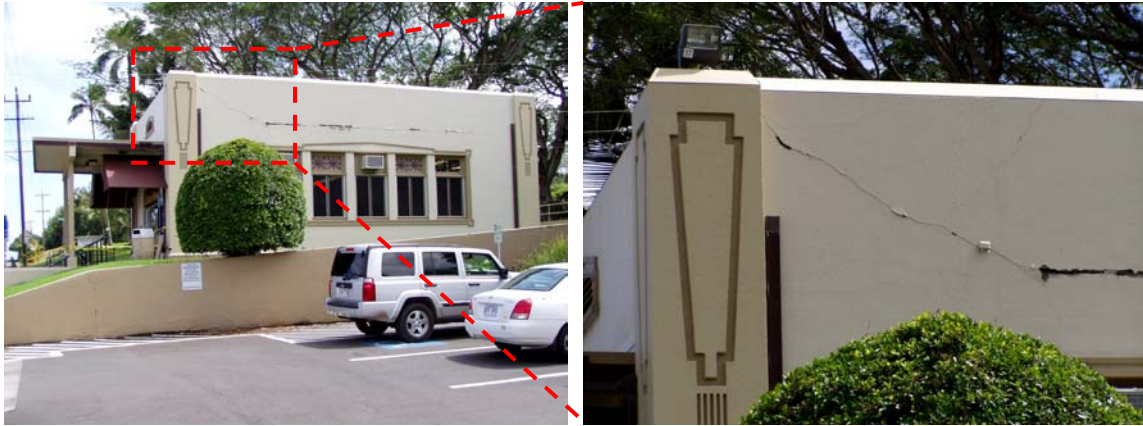


Figure 12: Horizontal and diagonal cracks in concrete walls of Bank of Hawaii in Kapaau, near Hawi (B2).

Nihon Restaurant

The Nihon Restaurant in Hilo consists of a two-story reinforced concrete structure with partial infill masonry walls at the ground level (Figure 13). Circular reinforced concrete columns and rectangular concrete beams at the first elevated level form a moment-resisting frame (MRF) for the first structural level. This MRF is relatively flexible compared with the infill masonry walls. No gap was provided between the walls and the frame to allow for this movement, resulting in diagonal cracking of the infill walls (Figure 14). Only minor cracking was noted at some of the MRF connections indicating that the building is structurally sound. The infill walls can be repaired and consideration should be given to providing a separation joint between the walls and surrounding columns and beams.



Figure 13: Nihon Restaurant, Hilo (B3).

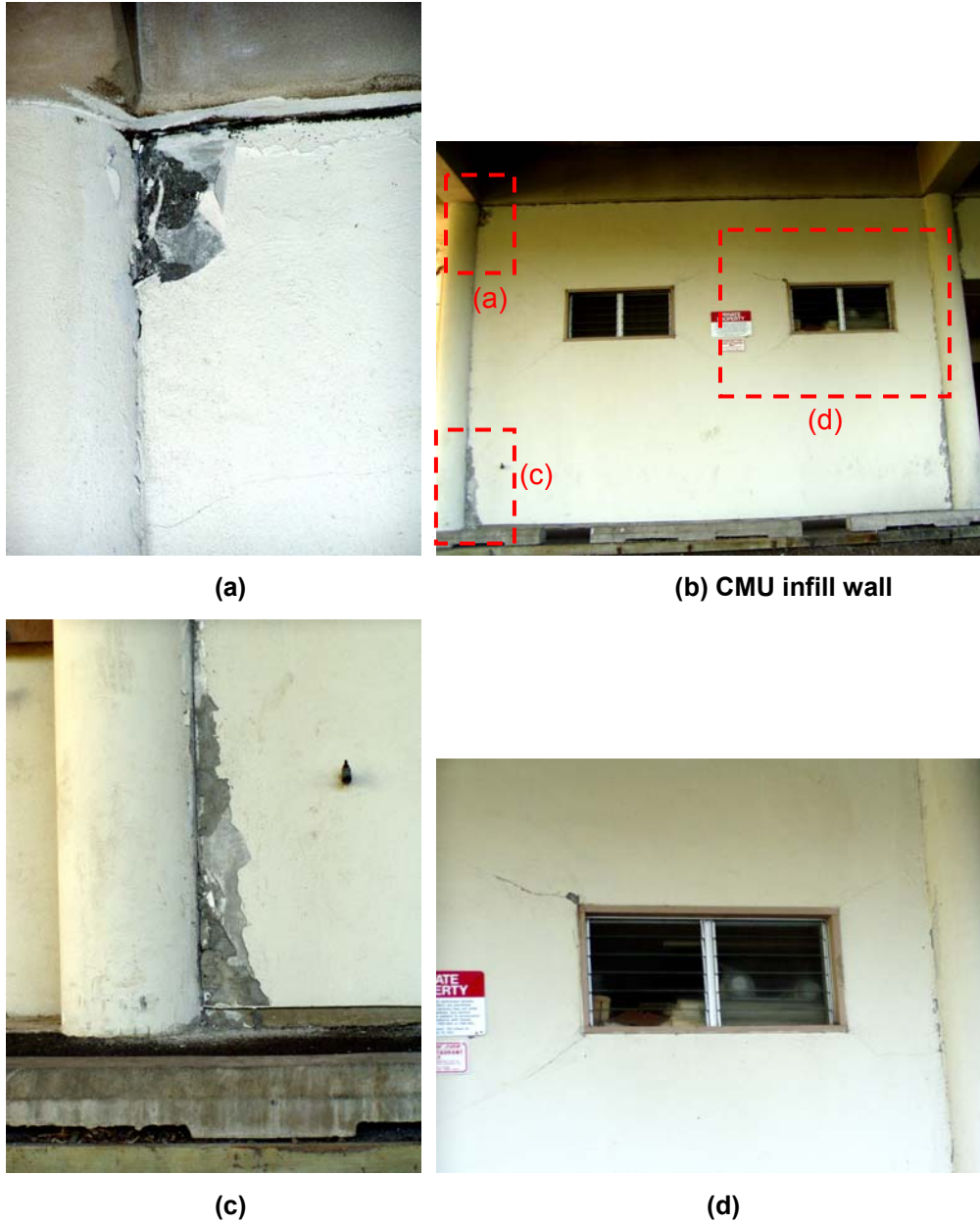


Figure 14: Damage to CMU infill wall due to flexibility of surrounding frame (B3).

Medical Facility in Honokaa

The Hale Ho'ola Hamakua medical facility in Honokaa suffered non-structural damage in the form of fallen stucco ceilings under the exterior roof eaves (Figure 15). Interior ceiling panels were also observed to have fallen in the lobby area. No structural damage was evident during our inspection of the building.



Figure 15: Damage to exterior stucco ceilings at Hale Ho'ola Hamakua medical facility in Honokaa (B4).

Kona Community Hospital (B5).

The Kona Community Hospital reported primarily non-structural damage in the form of fallen ceilings, light fixtures and other non-structural elements. These failures are attributed to the lack of adequate seismic bracing for non-structural components. Structural damage consisted only of minor cracking of reinforced concrete framing members (personal correspondence from Glenn Miyasato). All patients were relocated immediately after the earthquakes. Our team did not inspect this building.

Waikaloa Elementary School

Along with a number of schools in Waimea and Honokaa, the elementary school in Waikaloa suffered considerable non-structural damage (Figure 16). Many classrooms remain closed at the time of writing this report because of fallen ceilings, light fixtures and other non-structural items. Virtually no structural damage was reported at these schools.



Figure 16: Waikaloa Elementary School, closed due to non-structural damage (B6).

Non-Engineered Buildings

Kalahikiola Church

The historic Kalahikiola Church in Hawi, North Kohala, suffered extensive damage to the exterior rock-masonry walls supporting the roof trusses (Figure 17). Total collapse of the roof system appears to have been prevented by a single line of interior columns supporting the center of each roof truss and door and window frames supporting the eaves (Figure 18). The unreinforced rock-masonry walls were grouted with low-strength mortar, similar to many other rock-masonry walls built in the 19th and early 20th centuries (Figure 19). Many of these walls suffered damage in the form of cracking, partial collapse or complete collapse. The timber-framed bell tower appeared to have survived the earthquake with limited damage.



Figure 17: Kalahikiola Church in Hawi (B7).



Figure 18: Roof trusses supported by interior columns and window frames after wall collapse (B7).



Figure 19: Unreinforced rock-masonry walls grouted with low strength mortar (B7).

Hulihe`e Palace

The historic Hulihe`e Palace in Kailua-Kona on the West side of the Island of Hawai`i suffered significant damage and was deemed unfit for use by State Civil Defense officials (Honolulu Advertiser, October 21, 2006). Typical diagonal cracking occurred in the exterior walls of the building, particularly around door and window openings (Figure 20). Our team did not inspect this building.



Figure 20: Hulihe`e Palace in Kailua-Kona (Photo by Gary Chock) (B8).

Residential Buildings

A common system for residential construction in Hawaii up until the mid-1970's consists of timber-framed single-story buildings elevated above grade on pier-and-beam framing (Figure 22a). The wall framing of the residence is often "single-wall" construction, where a single layer of tongue-and-groove vertical siding planks act as load-bearing walls supporting the roof framing (Figure 21). The pier-and-beam framing supporting the first floor typically consists of numerous 4x4 timber posts supporting 4x6 or 4x8 floor beams which in turn support the 2x6 or 2x8 floor joists. The 4x4 posts are usually provided with 2x4 knee-braces in both orthogonal directions to prevent racking of the crawl space during wind or seismic loading (Figure 22c). The posts are supported on small concrete blocks locally known as "tofu blocks" which in turn rest on 18"x18"x9" unreinforced

concrete foundation blocks bearing on the in-situ soil (Figure 22b). In most cases, no connection is provided between the foundation block, “tofu block” and 4x4 post, though some buildings have uplift ties to resist wind-induced uplift.

Many buildings of this type survived the earthquakes. However, if the relative movement between the 4x4 posts and the supporting foundation exceeds the size of the “tofu block”, or successive shaking leads to “walking” of the posts, the building may fall off the foundations (Figure 23). In some cases, the building will collapse and be totally destroyed, however some buildings may survive the fall, though utility and plumbing connections will likely rupture. It may be possible to reposition some of these damaged residences on their foundations and effect repairs. However, it would be prudent to provide suitable retrofits to stabilize these pier-and-beam foundation systems against future ground-shaking.

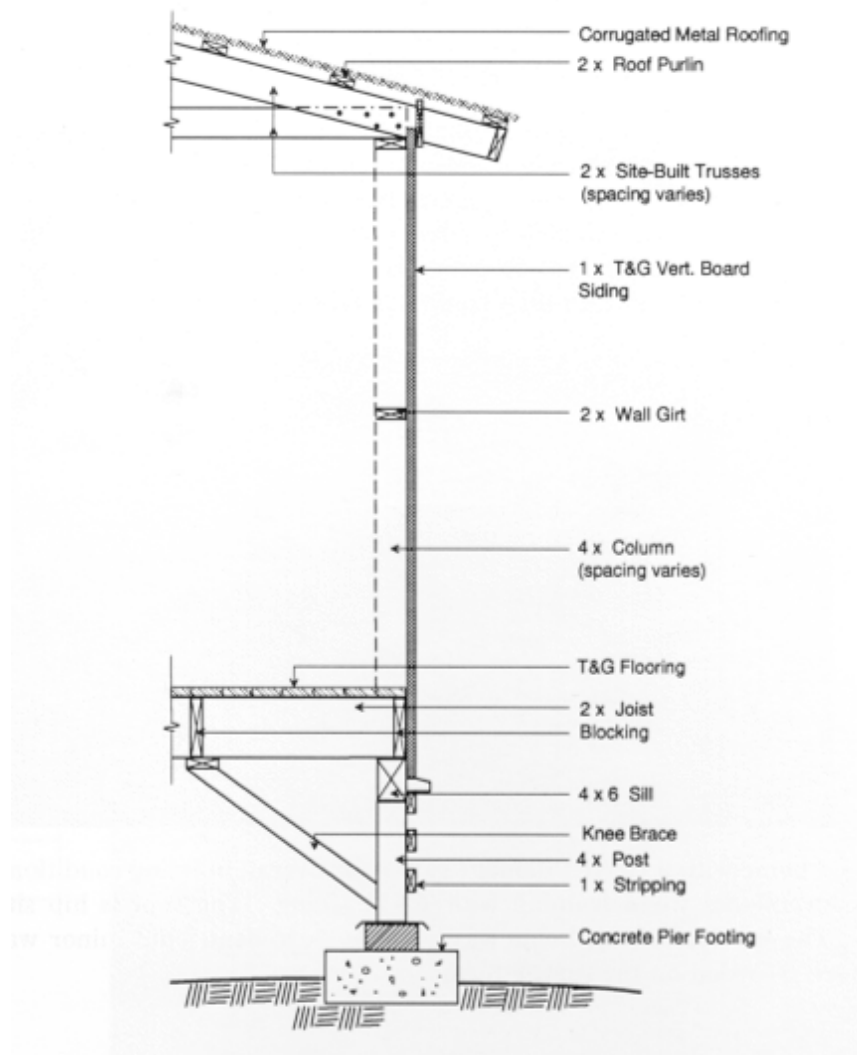


Figure 21: Section through “single-wall” construction on Pier-and-Beam foundation

Figure 22 shows a typical single-wall residence near Hawi that has shifted on its foundation, but remains intact.

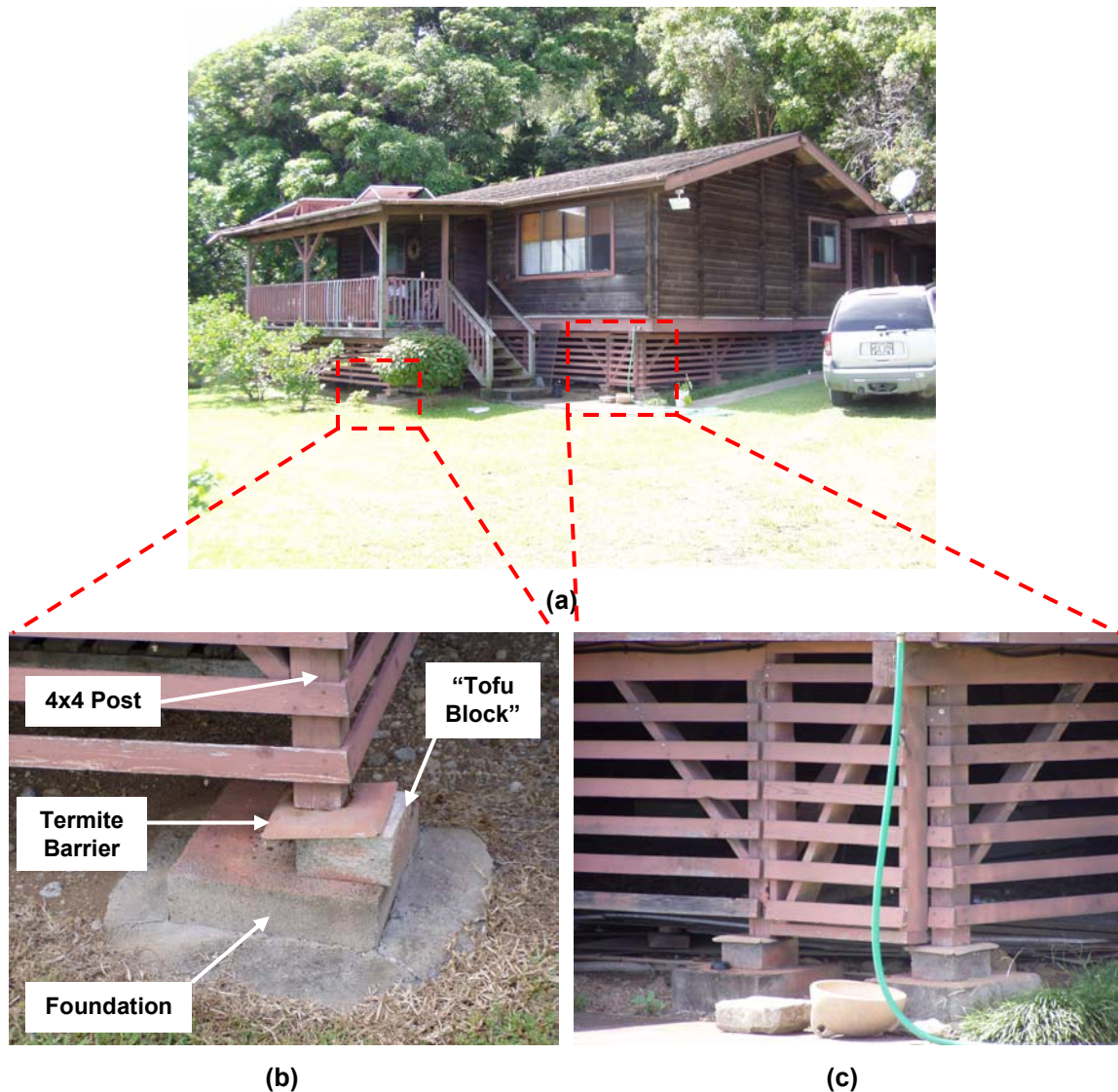


Figure 22: Typical timber framed residence at Pololu Valley Lookout on pier-and-beam construction (B9).

Figure 23 shows a typical single-wall pier-and-beam residence in Waimea that has shifted off its foundation blocks, resulting in damage to the support posts and the roof and wall framing. The owner plans to repair the residence.

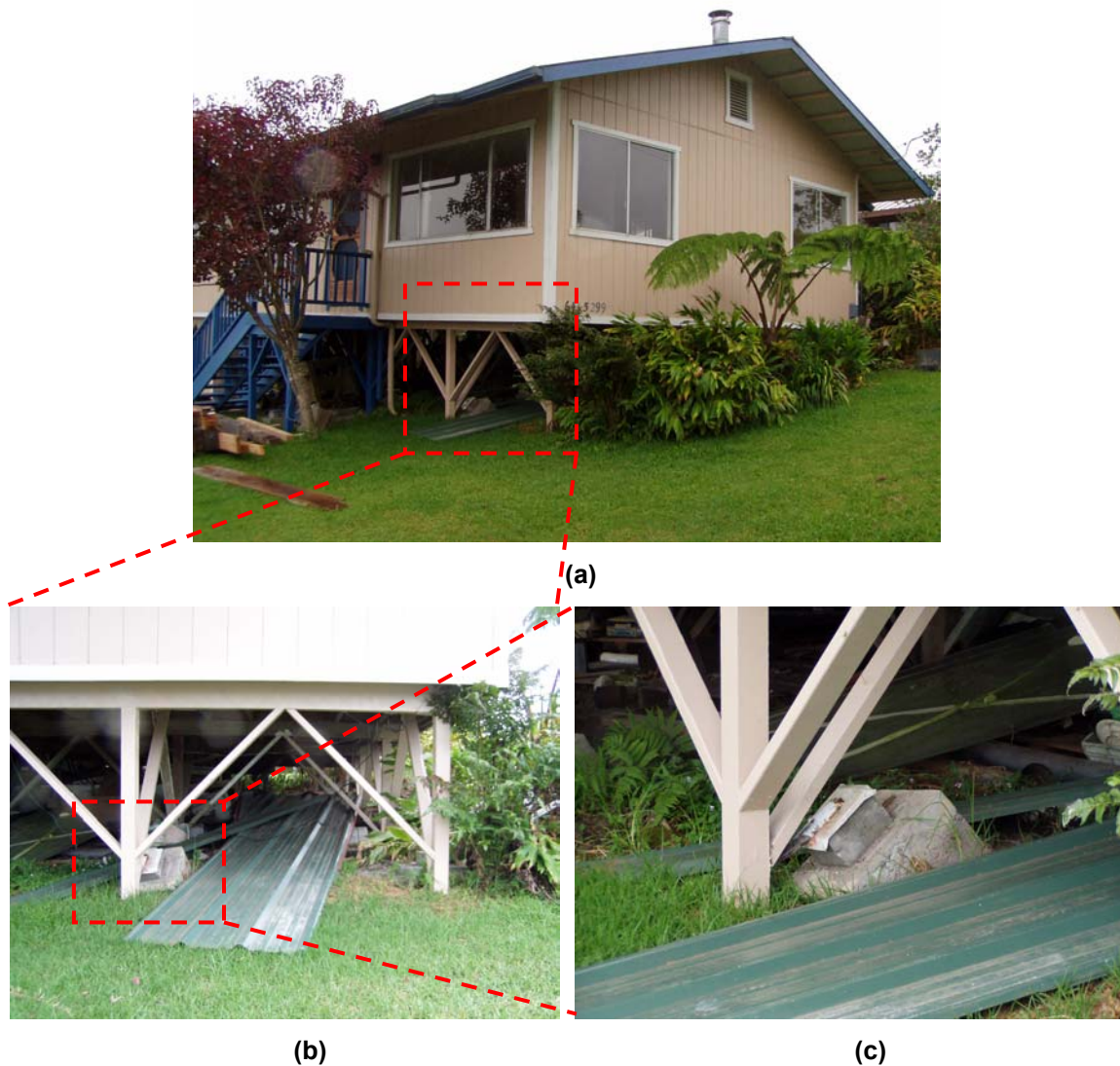


Figure 23: Pier-and-Beam residence in Waimea had fallen off its foundation blocks (B10).

Bridges

At the time of the writing of this report, it appeared that only two bridges suffered major damage during the earthquakes, requiring closure of one or more traffic lanes. One of these bridges is on the Island of Hawai'i (Honokoa Bridge – one lane closed) while the other is on Maui (Pa'ahi Bridge closed). A number of bridges exhibited minor spalling and other signs of pounding at abutments or between bridge segments, indicating appreciable movement of the superstructure during the earthquakes. These bridges all remained open to traffic at the time of writing this report. Four bridges were inspected during this reconnaissance trip as described below.

Honokoa Bridge

The Honokoa bridge, built in 1965, is located just North of Kawaihae on the West coast of the Island of Hawai'i. It is within 24 km (15 miles) of both earthquake epicenters. The bridge consists of two spans of simply-supported AASHTO prestressed concrete bridge girders supporting a reinforced concrete bridge deck (Figure 24). Figure 25 shows a schematic of the bridge cross-section. Significant damage was noted to the webs of the AASHTO girders at the abutments (Figure 26). Evidence of relative movement and pounding between bridge segments and between the bridge deck and the abutments was apparent from spalling damage to the bridge guardrails (Figure 27).



Figure 24: Honokoa Bridge (S1).

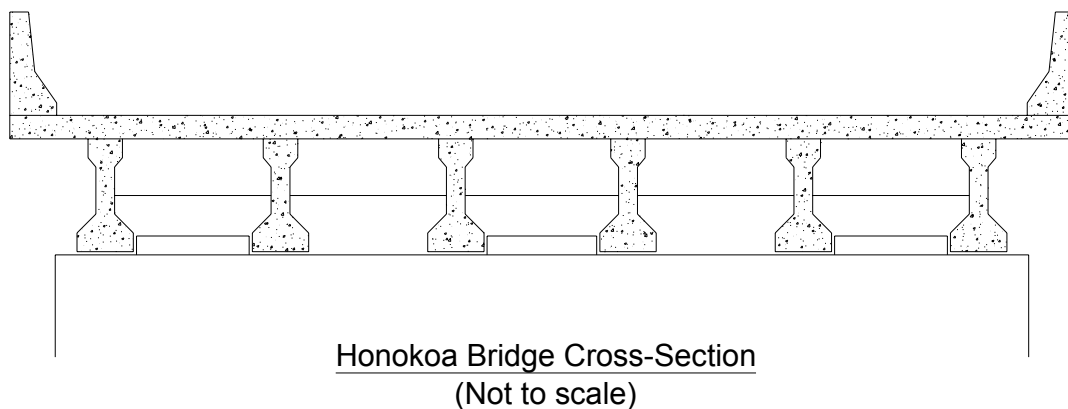


Figure 25: Cross-section through Honokoa Bridge.



Figure 26: Damage to web of AASHTO girder at abutments (S1).



Figure 27: Concrete spalling due to relative movement between bridge segments (S1).

It appears that the longitudinal motion of the bridge was effectively resisted by pounding against the abutments, while transverse motion was prevented by concrete shear keys between the bottom bulbs of the bridge girders (Figure 28).

Unfortunately, the bulkhead or bridging beams at the supports were only partial depth (Figure 28) and did not extend to the bottom bulbs. Therefore, lateral restraint of the

bridge deck had to transfer through the relatively thin girder webs, resulting in high transverse shear and flexural stresses for which the webs were not adequately designed. The bottom edge of the bridging beams showed a tendency to separate from the webs because of the large transverse inertial forces.



Figure 28: Shear key and bridging beam between AASHTO bridge girders (S1).

Personal correspondence with the State Bridge Engineer indicated that this bridge was scheduled for a seismic retrofit which was to include extending the bulkhead to the bottom of the girders. This retrofit had already been performed on three similar bridges on the Island of Hawai'i, none of which experienced damage during the earthquakes.

Kealakaha Stream Bridge

The Kealakaha Stream Bridge is a multi-span reinforced concrete girder bridge supported on two abutments and 5 reinforced concrete bridge bents founded in the deep gulch below the bridge (Figure 29). Because of seismic and operational deficiencies, the bridge is scheduled for complete replacement by a new three-span prestressed concrete bridge structure anticipated to start construction in early 2007. Although some distance from the epicenters of the October 15th earthquakes, there are signs of pounding between the bridge deck and the supporting abutment at the North end of the bridge (Figure 30). New cracking was noted in the corner of the abutment (Figure 31) and spalling had occurred at a number of the concrete pivot supports below the bridge girders (Figure 32). Some of these spalls appeared to have been initiated due to corrosion or other factors, but they were dislodged by the earthquake ground shaking. A minor slope failure was noted adjacent to the North abutment, but did not appear to affect the abutment stability. The bridge remains open to traffic.



Figure 29: Kealakaha Stream Bridge (S2).



Figure 30: Spalling of guardrail adjacent to North abutment (S2).



Figure 31: Crack in North abutment of Kealakaha Stream Bridge (S2).



Figure 32: Concrete spalling at girder supports at North abutment (S2).

Steel Trestle Bridge

A number of bridges along the island beltway (Route 19) North of Hilo consist of complex steel lattice construction typified by the bridge shown in Figure 33. These bridges have all been analyzed per current AASHTO seismic design provisions and retrofitted when deemed necessary. An example of the retrofit is the addition of restraint cables to prevent unseating of the steel plate girders (Figure 34). A detailed inspection of this bridge structure was not performed during this reconnaissance trip. The bridge remains open to traffic, as do all similar bridges along Route 19.



Figure 33: Steel Trestle bridge on Route 19 North of Hilo (S3).



Figure 34: Cable restraint retrofit of bridge plate girder joint (S4).

Hilo Historic Bridges

A number of historic concrete bridges in Hilo were inspected briefly during this reconnaissance trip (Figure 35). No signs of damage were noted.



Figure 35: 1938 Keawe-Wailuku Arch Bridge in Hilo (S4).

Harbors

The Island of Hawai'i is serviced by two ports, Hilo Harbor and Kawaihae Harbor. The vast majority of materials entering and leaving the island travel through these ports. These two harbors comprise the total of all of the available commercial shipping for the Island of Hawaii. As such, these harbors and their ability to be operational after a large earthquake should also be considered lifeline facilities.

Kawaihae Harbor (H1) is within 24 km (15 miles) of the epicenters of both earthquakes, while Hilo Harbor (H2) is over 90 km (56 miles) from the two earthquake epicenters. Kawaihae Harbor experienced both geotechnical and structural damage due to the earthquakes, while no damage was identified at Hilo Harbor. No barges were in port at Kawaihae during the earthquake, and a barge scheduled to dock there later on the day of the earthquakes was diverted to Hilo Harbor for offloading of perishable items. After determination that Pier 2 at Kawaihae Harbor was still usable, minor repairs were made to level the approach slab-to-dock transition on October 17th. The barge returned to dock and completed unloading at Kawaihae Harbor on Wednesday, October 18th.

Liquefaction and Lateral Spreading

In an earthquake event of this size, the amount of shaking is sufficient to liquefy loose, cohesionless soils that are in a saturated state. This is most common in coastal areas where natural alluvial deposits are found. Liquefaction is also common in reclaimed fill particularly when constructed using dredged material or by hydraulic fill methods. At

least two significant areas of the Island of Hawaii are known to be susceptible to liquefaction. These are the Hilo Harbor area on the East side of the island and Kawaihae Harbor on the West side. Significant damage at Kawaihae resulted from liquefaction. Additionally, there was an unconfirmed report of a sand boil in Kailua-Kona. No liquefaction was observed or reported for the Hilo area.

Kawaihae Harbor was visited on both Tuesday and again on Wednesday following Sunday's earthquakes. Clear evidence of liquefaction was observed at Kawaihae Harbor in both the public marina and the commercial port facility. This area is known to contain significant depths of unconsolidated gravelly calcareous sand from adjacent dredging operations. In the public marina area, significant cracks displayed both vertical and lateral displacement of several inches. The shoreline protection provided by 1-3 ft boulders had moved out of alignment with spreading of an area approximately 20 feet from the water's edge. Figure 36 and Figure 37 show cracking and lateral spreading in the public marina. Numerous sand boils were evident in the unpaved parking area and adjacent grassed area up to 50 feet from the water's edge and to elevations of approximately 6 feet above the water level (Figure 38).



Figure 36: Liquefaction induced settlement and lateral spreading at public marina (H1).



Figure 37: Ground fissures evidencing lateral spreading at public marina (H1).



Figure 38: Sand boils at Kawaihae Harbor (H1).

The commercial port facility at Kawaihae Harbor consists of two pile-supported concrete piers, the older Pier 1 to the North and Pier 2 to the South, and an asphalt paved shipping container yard. Large areas of the asphalt yard, which is constructed over dredged fill, had settled up to approximately 6 inches (Figure 39 and Figure 40). Fine sand had been ejected from cracks in the asphalt pavement and through junctures between the paved fill area and the pile-supported concrete pier (Figure 41). A series of cracks with widths ranging from approximately 1/4 inch to several inches were observed roughly aligned parallel with the shoreline (Figure 42). Cumulatively, these cracks displayed lateral spreading of 6 inches or more. Personnel at the facility described fine sand and water “squirting out of the cracks” in the pavement immediately following the earthquakes. These personnel also described enlargement of the spreading cracks over a period of one to two days following the earthquakes.

Had there not been boulder-sized slope protection in the public marina area and massive pile-supported concrete piers in the port facility, there likely would have been more severe displacements throughout the harbor area. Pier 1 displaced as much as 6 to 12 inches laterally towards the harbor. This movement indicates that the piles were moved and/or distressed by the lateral spreading of the liquefied soil beneath and landward of the pier. This area will likely liquefy again in another strong earthquake if the soil is not densified or if no other mitigation measures are undertaken.



Figure 39: Liquefaction induced settlement at Kawaihae Harbor port facility. Pile supported pier on left, dredged fill beneath pavement on right (H1).

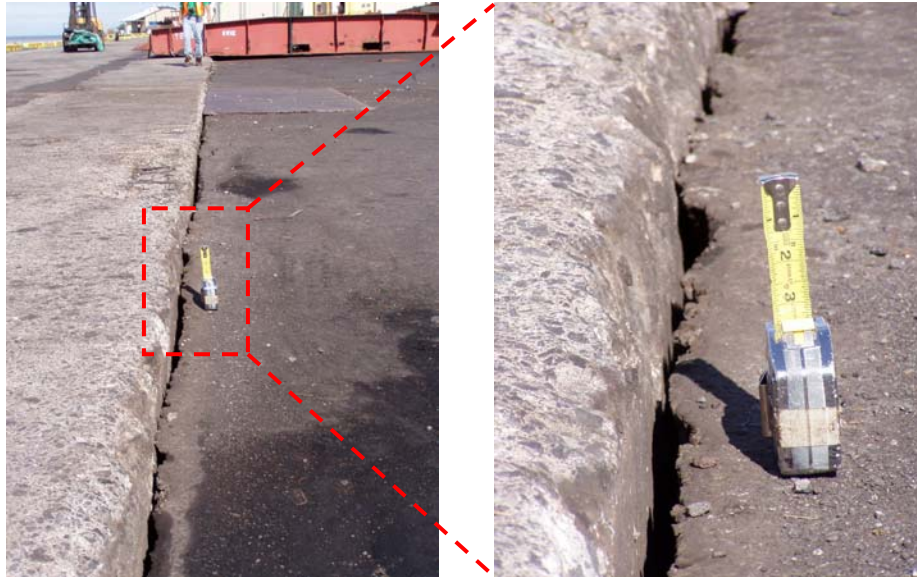


Figure 40: Liquefaction induced differential settlement between pile-supported pier on left and asphalt pavement on fill (H1).



Figure 41: Fine sand ejected through cracks in pavement as soil beneath liquefied at Kawaihae Harbor port facility (H1).



Figure 42: Several-inch gaps formed by relative displacement of pile-supported pier founded in liquefiable soils (H1).

Damage to the port facilities resulting from liquefaction included:

- total and differential settlement, as well as lateral displacements and associated separations within the shipping container yard (Pier 2). This damage created an immediate problem for loading/offloading of containers;
- the spreading of the shipping yard from the bulkhead and concrete pier also created serious concern for the fuel offloading pipelines which traversed the damaged area;
- damage to Pier 1 and adjacent apron forcing closure of this portion of the port. This had the additional consequence of inaccessibility of the pneumatic Hawaiian Cement offloading pipelines. This is the only facility for unloading cement to the island and thus represents a severe problem for the construction industry.

A cursory tour of the harbor area in Hilo was made on Wednesday following the earthquakes. No evidence of ground faulting or liquefaction was observed or reported along the shoreline. A closer inspection was made of the shipping port facility as it was considered a critical lifeline for the island. The shipping yard, which has been expanded into the harbor with dredged fill, has experienced significant and ongoing settlement problems for several years indicating soft and/or loose subgrade soils. The degree of ground shaking at the Hilo Harbor during these earthquakes was fortunately not strong

enough to cause liquefaction-induced settlement or lateral spreading. However, it remains a concern in the event of stronger shaking.

Structural Damage at Kawaihae Harbor

Pier 1 had significant damage as a result of the liquefaction and lateral spreading described earlier. The resulting seaward movement of the pile-supported pier resulted in torsional cracking of the large concrete beam along the edge of the pier. Major torsional and longitudinal cracks were noted in this beam as shown in Figure 43(b), (c) and (d). Separation between the edge beam and concrete approach slab was not controlled by the ineffective and corroded dowel bars shown in Figure 43(e). It is unknown whether there was any damage to the piles supporting the pier and this edge beam.

Although Pier 2 had moved slightly seaward because of liquefaction and lateral spreading of fill material under the approach slab, there was no evidence of new cracking of the elevated concrete pier slab and beams due to the earthquakes. It is unknown whether there was any damage to the piles supporting this pier.

Three warehouses on Piers 1 and 2 are constructed of pre-manufactured metal frames with sheet metal cladding (Figure 44). Since the seaward columns are all supported on the concrete piers, while the landward columns are supported on foundations in the fill material below the approach paving, the metal frames had spread to accommodate the lateral movement of the piers. Figure 45 shows the resulting opening in the unreinforced concrete masonry unit (CMU) wall at the South side of one of these warehouses on Pier 1. The interior view of this warehouse shows that the column lateral movement resulted in shear failure of the two bolts securing the end of the first horizontal girt (Figure 46).

The warehouse on Pier 2 did not appear to be adversely affected by the lateral spreading, however, one diagonal brace member had separated at the adjustment turnbuckle as shown in Figure 47. It appeared that only two threads of the bracing rod had been engaged with the turnbuckle, resulting in stripping of these threads during the ground shaking.

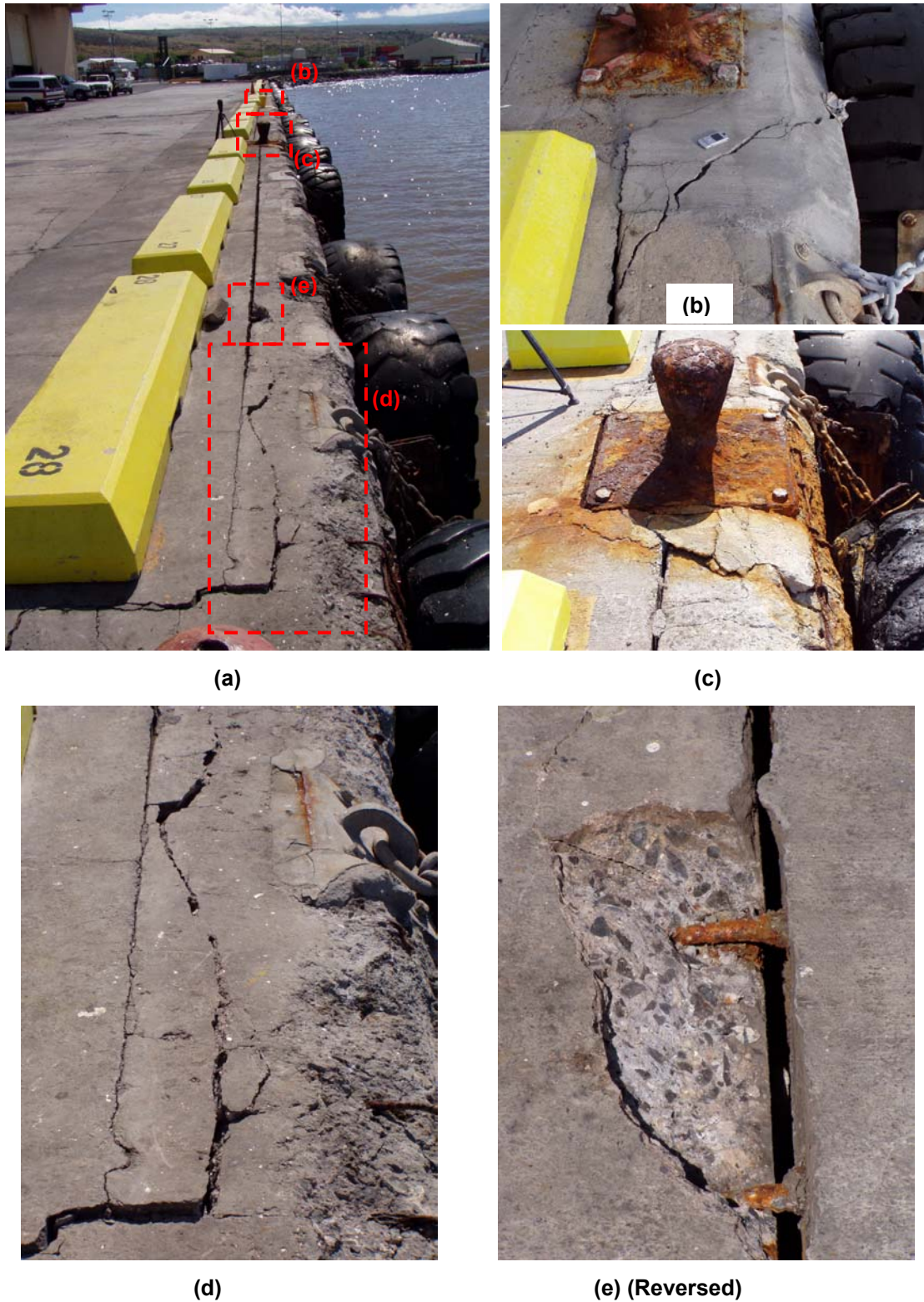


Figure 43: Torsional cracking in edge beam at Kawaihae Harbor Pier 1 (H1).



Figure 45

Figure 44: Warehouse at Kawaihae Harbor Pier 1 (H1).



Figure 46

Figure 45: Separation in CMU wall at corner of warehouse (outside and inside views) (H1).



Figure 46: Shear failure of bolts securing girt to corner column (H1).



Figure 47: Failed diagonal brace at North end wall of warehouse on Kawaihae Harbor Pier 2 (H1).

Dams

Reservoirs closest to the location of the earthquake, i.e. those in the Waimea area, were inspected for signs of damage. Of greatest concern was the series of Waikoloa water supply reservoirs that are perched on a mountainside between 500 and 1000 feet above the town of Waimea-Kamuela. A total of four connected reservoirs hold nearly 200 MG (million gallons) of water. They all consist of circular or elongated pool structures surrounded by earth fill embankments, with portions excavated into the sloping hillside. The inside of each reservoir is lined with concrete panels that reach up to the crest of the embankment. Our inspection two days after the earthquake revealed evidence of severe shaking in the topmost reservoir (the 60MG Waikoloa II, Figure 48). It appears that the circular earth embankment may have displaced laterally, as evidenced by disturbance of fill on the crest adjacent to the top of the concrete panels (Figure 48). The ring of disturbed soil reflects relative movement between the concrete panels and the crest of the embankment. Absolute displacements may have been even larger. Cracks 2 to 4 inches wide and up to 2 feet deep were noted as well (Figure 49). The damage extended over a section spanning about 240 degrees around the embankment circumference and indicated a strong motion component in the East-West direction. The portion of the embankment located facing the downhill side of the mountain saw the least amount of damage.



Figure 48: Waikoloa II reservoir showing lateral displacement of top of embankment (D1).



Figure 49: Cracks on top of embankment adjacent to concrete liner panels (D1).

Despite the observed damage due to horizontal motions, no significant permanent lateral shifting of the overall embankment was discerned. The extent of horizontal motions during cyclic shaking compare to predicted displacements of less than a tenth of a foot from numerical dynamic modeling carried out as part of an earlier investigation, which utilized conventional equivalent-linear response analysis along with site-specific soil properties and a nearby earthquake record from an earlier event scaled to accelerations less than 0.2g. That particular analysis also showed substantial amplification of ground motions at the crest of the embankment.

Two transverse cracks on the crest of the embankment, separated by 3 to 4 feet, were each about ½ inch wide and of unknown depth (Figure 50). The area between these cracks was noticeably softer than adjacent portions of the embankment. Joints between some of the concrete panels opened up somewhat. Some spalling was noted along the upper lip of the concrete lining (Figure 51). Seepage through the embankment was known to occur from prior surveys. Our inspection did not reveal any additional seepage from the reservoir through the embankment that may have been associated with the earthquake. Inlet and outlet structures seemed to have fared well.



Figure 50: Transverse crack on embankment top (D1).



Figure 51: Concrete spalling, cracking and opening of panel joints (D1).

Similar observations were made with regard to the adjacent Waikoloa I reservoir (Figure 52), but signs of severe shaking were significantly less. There was some fill disturbance near the top of the concrete lining, but only along two 50 foot-long sections on opposite sides of the pool. The other reservoirs in the series showed no evidence of significant damage. The water treatment plant below the reservoirs did show some distress, consisting chiefly of cracks in soil slopes, some ruptured PVC pipes and shifting/cracking of concrete works.



Figure 52: Waikoloa I reservoir indicating extent of observed fill disturbance (D1).

The other major reservoir system in the area consists of the circular Waimea 60MG reservoir, which is connected to the 120 MG Puu Pulehu reservoirs by a buried pipe. The latter reservoir developed significant cracking where the crest of the embankment transitions to the outside slope (Figure 53 and Figure 54). Damage occurred along the steepest portion of the embankment (about 1H:1V or somewhat steeper), with the system of cracks extending some 135 feet parallel to the crest. Displacements of the cracks showed both lateral and vertical components of approximately 2 inches at the surface, clearly indicating incipient slope failure. Even larger cracking of the same nature was reported for the Paauhilo reservoir, located further away from the epicenter.



Figure 53: Downstream slope of Puu Pulehu reservoir embankment (about 1H:1V) (D2).



Figure 54: Cracks in crest of Puu Pulehu embankment (D2).

The Waimea reservoir fared relatively well, except for some minor sliding of the rock rip-rap on the inside slope of the embankment (Figure 55), along with cracks in the soil beneath (Figure 57). Some of the ditches that feed these reservoirs were blocked by debris and suffered damage that made them inoperable for a few days.



Figure 55: Waimea 60MG reservoir showing concrete and rip-rap lining (D3).



Figure 56: Sliding of rock rip-rap lining at Waimea Reservoir (D3).



Figure 57: Cracks in reservoir embankment beneath rip-rap (D3).

Roadways, Rockfalls and Landslides

Numerous rockfalls and landslides occurred as a result of the two large earthquakes and their aftershocks. Although many of these were associated with roadway cuts and embankments, some very large debris and rockfalls occurred on steep cliffs such as in Kealahou Bay and on the North Kohala coast in the series of deep valleys between Pololu and Waipio. These latter valleys are only accessible by foot and are largely uninhabited. Therefore damage to infrastructure from these remote slides, which in some cases involved substantial amounts of material descending many hundreds of feet by free falling, bouncing and rolling, was minimal, except for damage to hiking and mule trails. Most of the slides between Pololu and Waipio remain to be assessed. A number of sea cliffs along the Hamakua coast between Honokaa and Hilo also saw sliding. Several similarly long, narrow and shallow slides were observed along Highway 19 on the Hamakua coast, South of Waipio valley, particularly where the road descends into three deep erosional valleys with steep flanks (Maulua, Laupahoehoe and Kaawalii gulches) (Figure 58). These slides originated high above the road in naturally steep terrain. In general, large landslides were confined to areas North of Kailua-Kona and

North of Hilo. In at least one instance, a landslide resulted in damage to a residential structure (Figure 59).

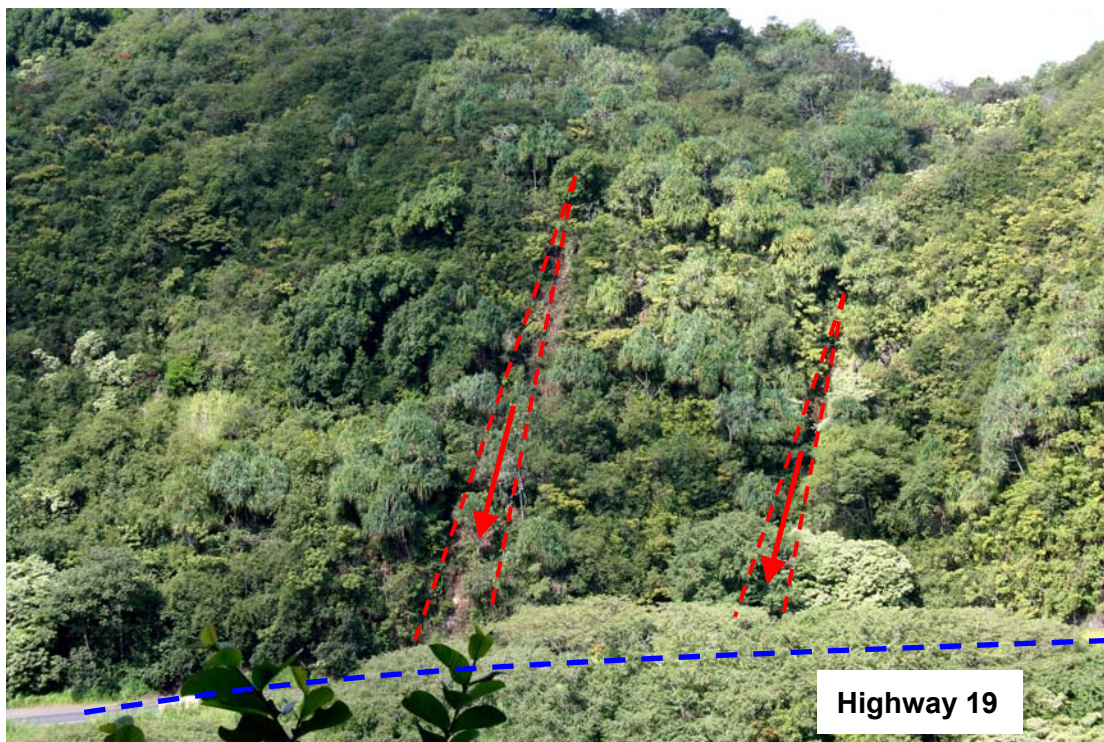


Figure 58: Long, narrow slides on natural slope above roadway (R1).



Figure 59: Slide near damaged residence on Hamakua Coast (R2).

Dozens of smaller slides and rockfalls were observed along highway road cuts. Virtually every steep road cut North of Kailua-Kona and North of Hilo exhibited some degree of rockfall or debris slide (Figure 60 and Figure 61). The most severe falls appeared to be where very steep cuts (significantly greater than 1H:1V) had been made. In particular, large boulders fell where there was a noticeable layering of volcanic rock strata with dense, blocky basalt overlying more friable pyroclastic tuff, ash and clinker. The underlying weaker layers typically consist of smaller rock units, which are less resistant to shearing and therefore provide minimal stability with respect to lateral loading. An example of the layering and discontinuity between the dense and clinker layers is shown in Figure 62. Many of these rockfalls and slides blocked travel lanes. In several cases, roadways became impassable (Figure 63). For many locations on the island, one or two road closures essentially cut those areas off from access by emergency or supply vehicles and make any necessary evacuation very difficult. As such, these roadways are important lifelines in the case of an emergency. Fortunately, as a result of this event, the extent of road obstructions from rockfalls and landslides could be cleared in a reasonably short period of time. Although not inspected by our team, rockfalls and slides were also reported along the East end of Maui that resulted in temporary closure of the Hana Highway. Two days after the October 15th earthquakes, all roadways on the Island of Hawaii had been sufficiently cleared to allow at least one-way traffic.



Figure 60: Rockfall in road cut at mile 35.5 on Highway 190 (R3).



Figure 61: Rockfalls on road cuts along Highway 19 North of Kailua-Kona (R4).



Figure 62: Example of discontinuous geology where dense basalt rock overlies weaker and less stable clinker (R3).



Figure 63: Example of single road access to northern end of North Kohala that was temporarily closed due to sliding; one-lane bridge in background (R5).

Two important observations were made regarding rockfalls and landslides that affected roadways. Instabilities occurred in nearly every road cut steeper than 1H:1V, but they were significantly less prevalent in cuts that were less steep. The resting configuration of many cuts into rock approached 1H:1V after sliding. With regard to roadways as crucial transportation links, a wide shoulder (such as along Highway 19 on the Kona coast) is crucial to accommodate rock and debris waste and thus maintain the road's function as a critical lifeline (Figure 64).



Figure 64: Rockfall onto shoulder of Highway 19 North of Kailua-Kona (R6).

Although rock and soil slides in cuts above roadways were numerous, damage to road embankments and pavements was less prevalent, with a few exceptions. The most dramatic of these was the collapse of half of the roadway at Mile 35 on Highway 19,

resulting in the closure of one lane of traffic (Figure 65 and Figure 66). This was caused by failure of a 20-foot high embankment and rock wing wall on the approach to a concrete girder bridge. The cast-in-situ concrete girder bridge is supported on rock wall abutments as shown in Figure 67. The bridge suffered no damage but the adjacent embankment failed. The wing wall consisted of mortared rock and was approximately 14 inches thick similar to the other side of the roadway (Figure 68). A number of unmortared rock walls collapsed elsewhere (Figure 69), while many well-built rock walls performed satisfactorily. One reinforced concrete retaining wall in Honokaa was observed to have failed due to poor foundation support (Figure 70).



Figure 65: Collapse of Highway 19 embankment on approach to bridge (R7).



Figure 66: Collapsed abutment wing wall (R7).



Figure 67: Collapse occurred around the right rear corner of rock wall abutment (R7).



Figure 68: Similar mortared rock wall on opposite side of collapsed embankment (R7).



Figure 69: Collapse of un-mortared and unreinforced retaining wall in Honokaa (R8).



Figure 70: Collapse of concrete retaining wall with inadequate footing in Honokaa (R8).

The parking lot at the Pololu lookout and the approach road at the end of Highway 270 experienced serious longitudinal cracks, on the order of 3 to 4 inches wide and 2 to 3 feet deep, which were associated with embankment instability on the down-slope side of the road (Figure 71 and Figure 72). Neighbors reported continued growth of the cracks since the first shaking on October 15th, perhaps due to the numerous aftershocks. Hikers returning from the valley below also reported large cracks in the trail leading down to the beach some 1000 feet below. As a result, both the parking lot and the trail have been closed indefinitely.



Figure 71: Cracks at Pololu lookout due to lateral sliding of road toward steep slope (R9).



Figure 72: Collapsed rock wall at end of Pololu lookout parking lot (R9).

At mile 14.5 on Highway 270 in North Kohala, an embankment and rock wing wall adjacent to a storm water culvert failed (Figure 73). A transverse crack was observed in the asphalt pavement adjacent to the end of the failed embankment (Figure 74). This was accompanied by an upheaval of asphalt near the center dividing line, which may suggest a moderate vertical component to the seismic motion.



Figure 73: Failed highway embankment and rock wing wall adjacent to culvert (R10).



Figure 74: Repaired transverse crack in pavement (R10).

Longitudinal cracking and shallow slope failure was also observed at mile 13 on Highway 190. Here the embankment was again relatively steep (at least 1H:1V), with the fill consisting of silty and sandy gravel. Due to the narrow shoulder, some of the asphalt along the edge of the road collapsed along with portions of the head of the embankment slope (Figure 75). At a few locations the pavement was left bridging cavities underneath.



Figure 75: Embankment and asphalt collapse at mile 13 on Highway 190 (R11).

Several other instances of minor road damage were also observed, as for example the head crack at the edge of the lookout at Mile 8 on Highway 250 (Figure 76). Such cracks were generally observed in moist weathered silty and clayey soils where slopes were 1H:1V or steeper. More extensive soil displacements tended to occur only in significantly steeper environments, such as on the flanks of deep gulches or on steep

mountainsides. As with other instances of earthquake-induced damage, road and embankment instability decreased with distance from the epicenter.



Figure 76: Incipient sliding in silty soil at crest of 1H:1V slope at milemarker 8 on Highway 250 (R12).

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Appendix A

Horizontal and Vertical Acceleration Records for Selected Strong-Motion Stations on Hawai`i

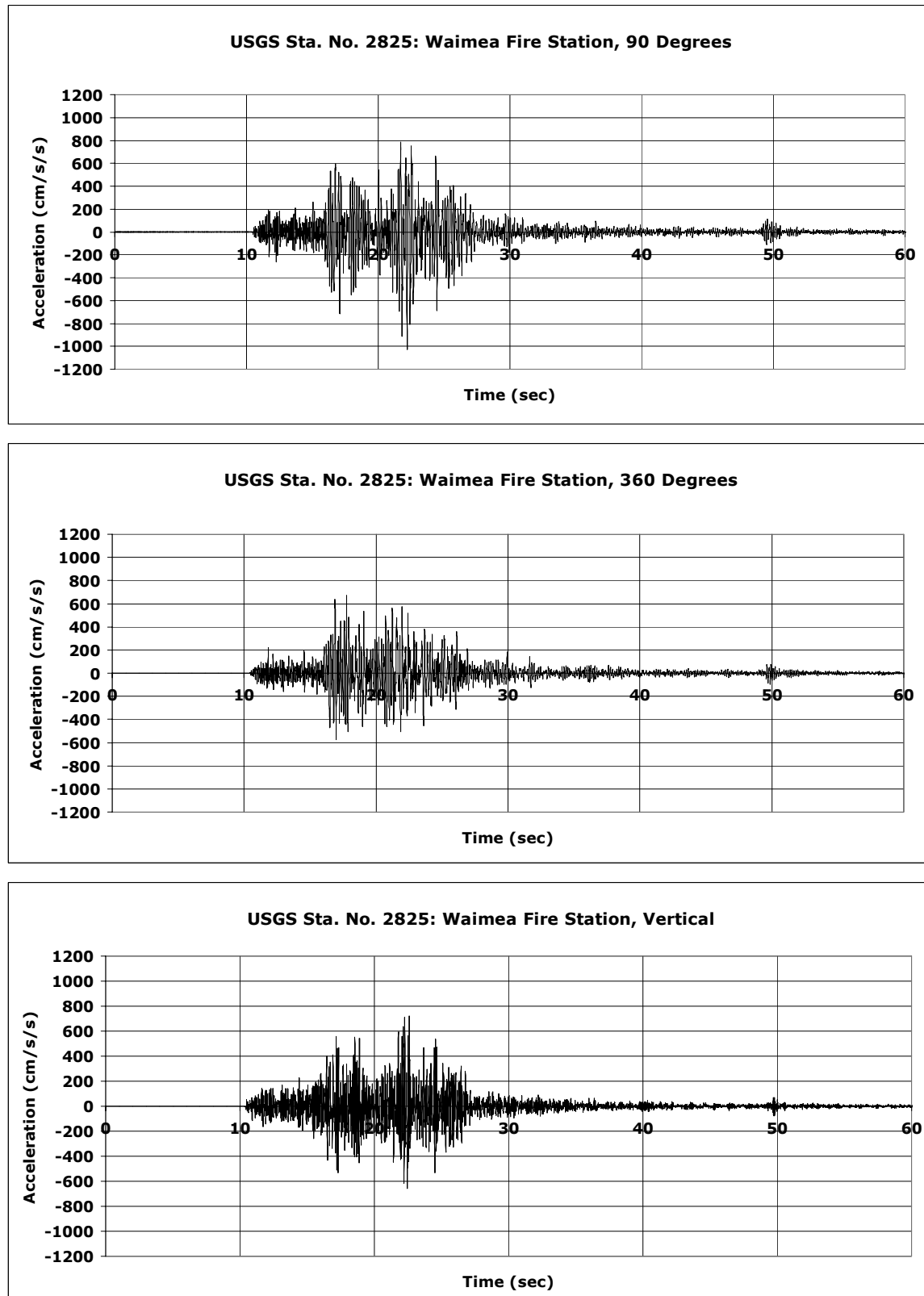


Figure A-1: SM records for Waimea Fire Station during Mw6.7 Kiholo Bay earthquake.

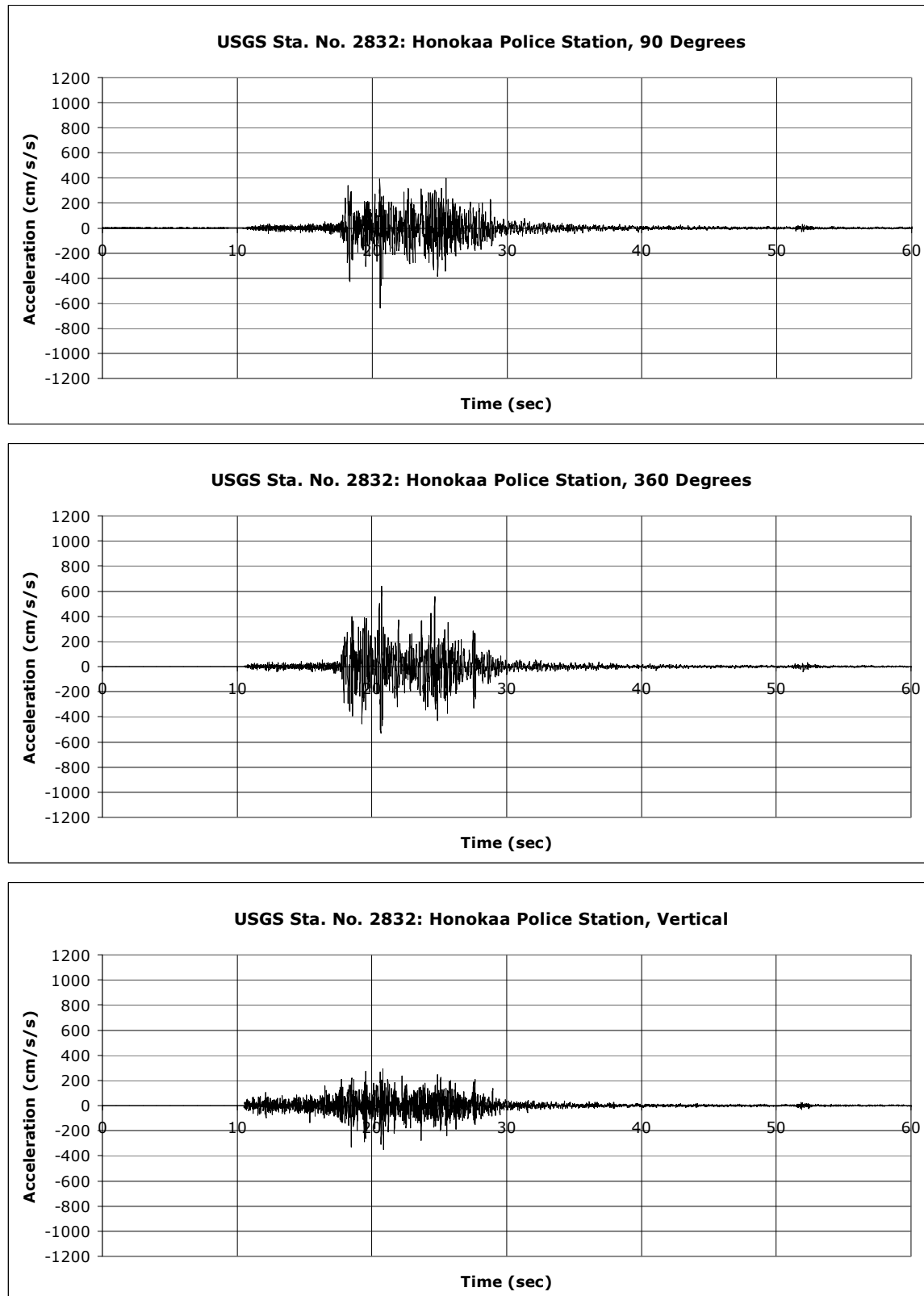


Figure A-2: SM records for Honokaa Police Station during Mw6.7 Kiholo Bay earthquake.

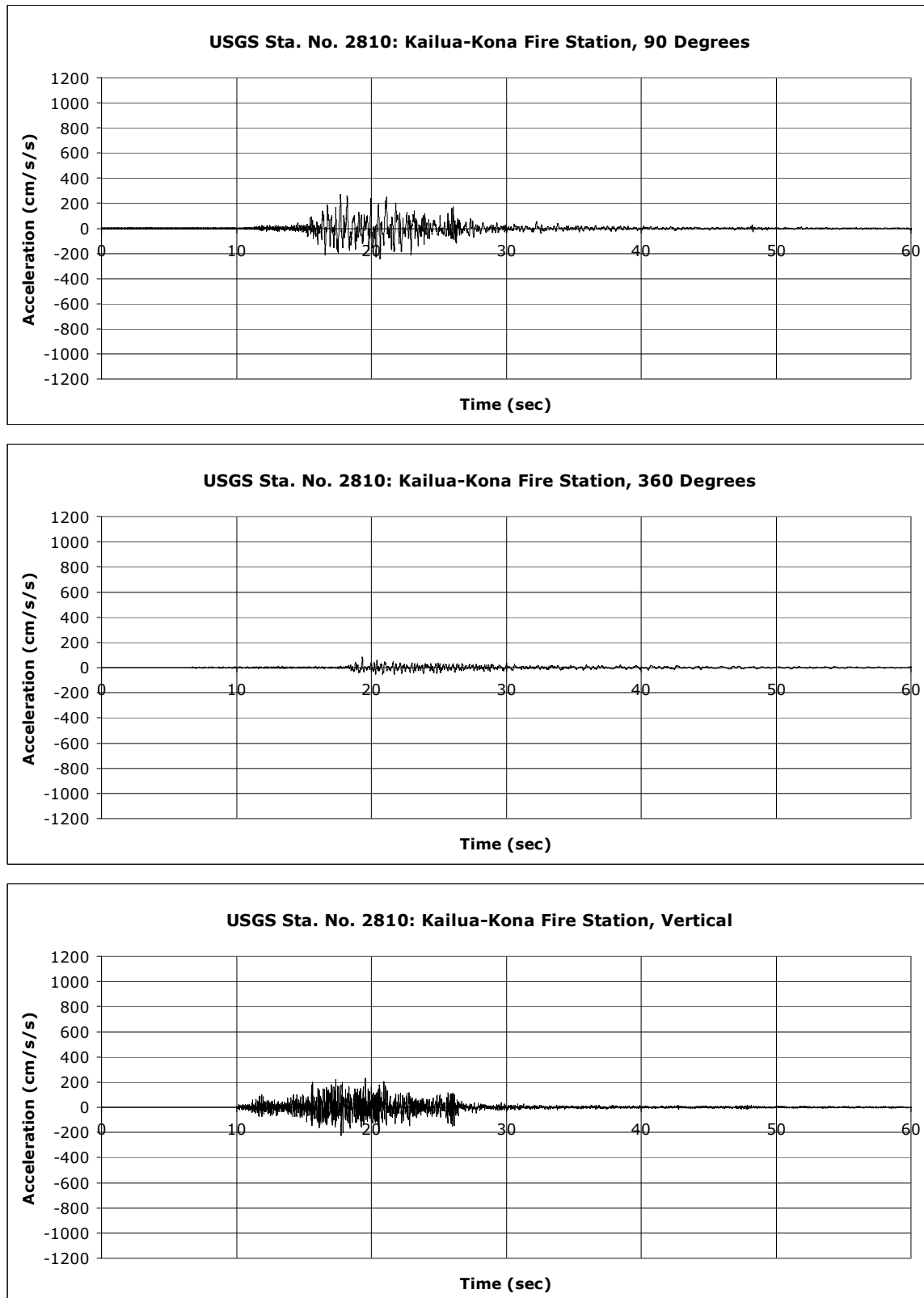


Figure A-3: SM records for Kailua-Kona Fire Station during Mw6.7 Kiholo Bay earthquake.

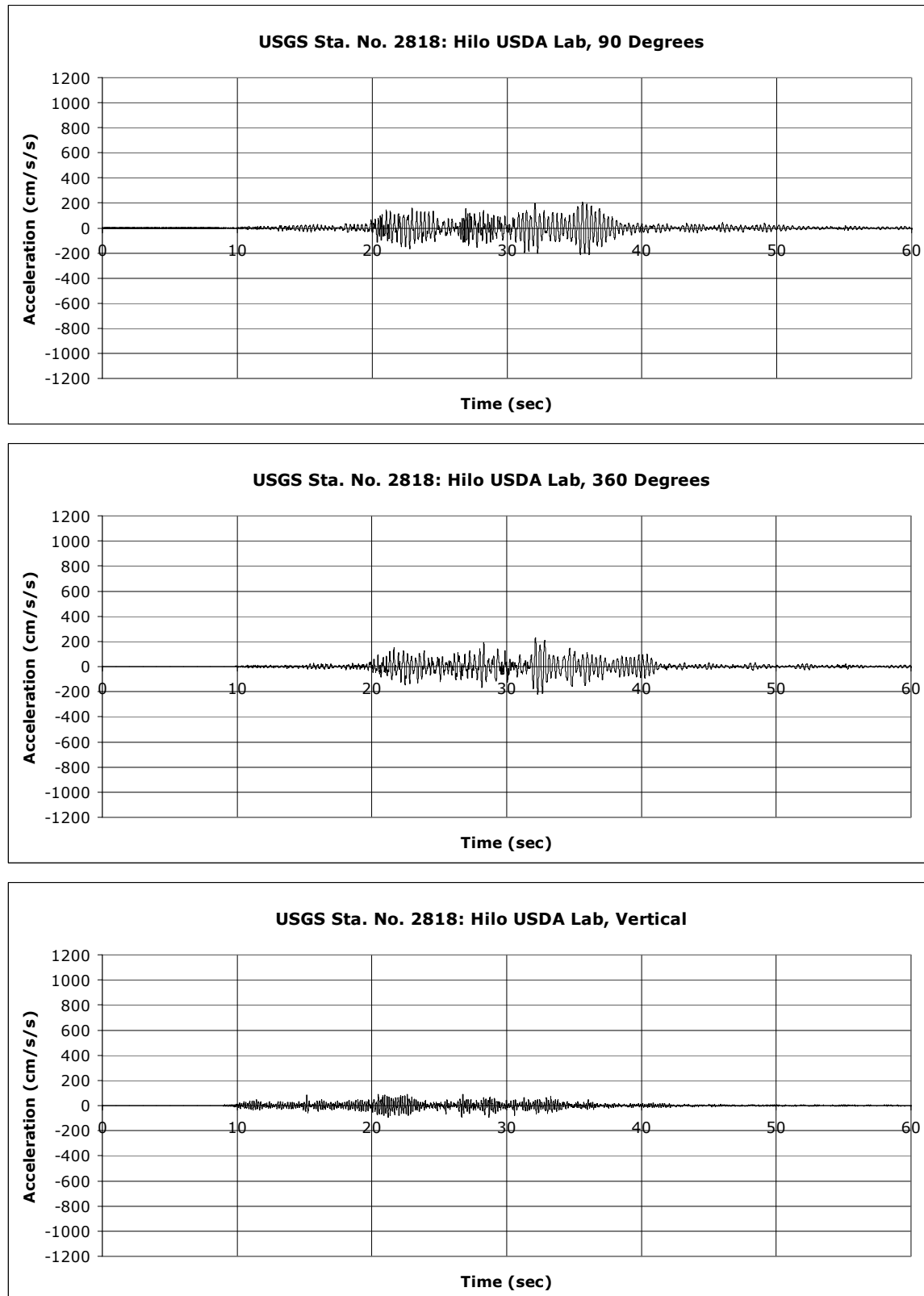


Figure A-4: SM records for Hilo USDA Lab during Mw6.7 Kiholo Bay earthquake.

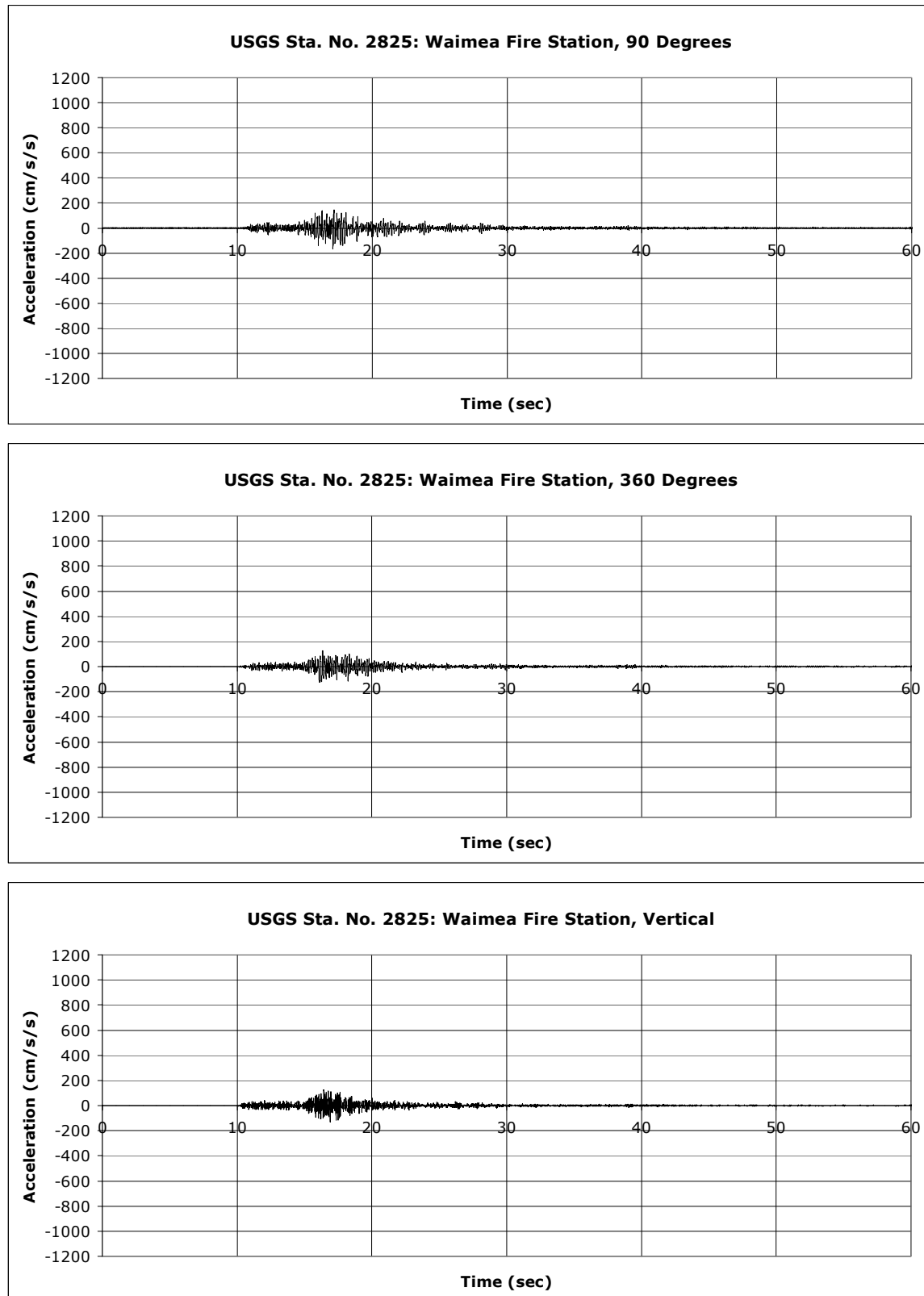


Figure A-5: SM records for Waimea Fire Station during Mw6.0 Hawi earthquake.